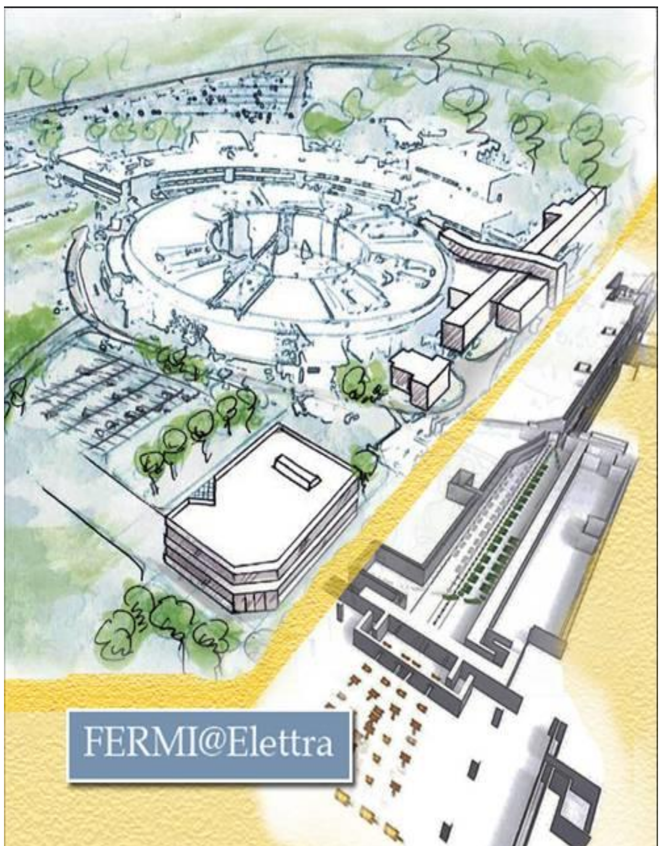
Elettra Sincrotrone Trieste

Elettra
Sincrotrone
Trieste

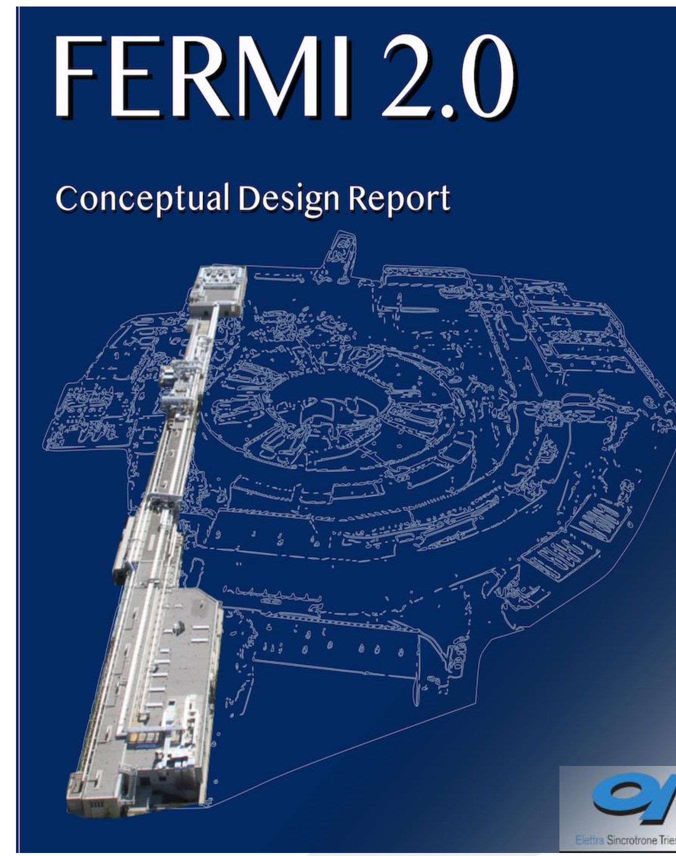
Fabrication & Commissioning of 1st HG Module



Nuaman Shafqat

on behalf of

FERMI Team



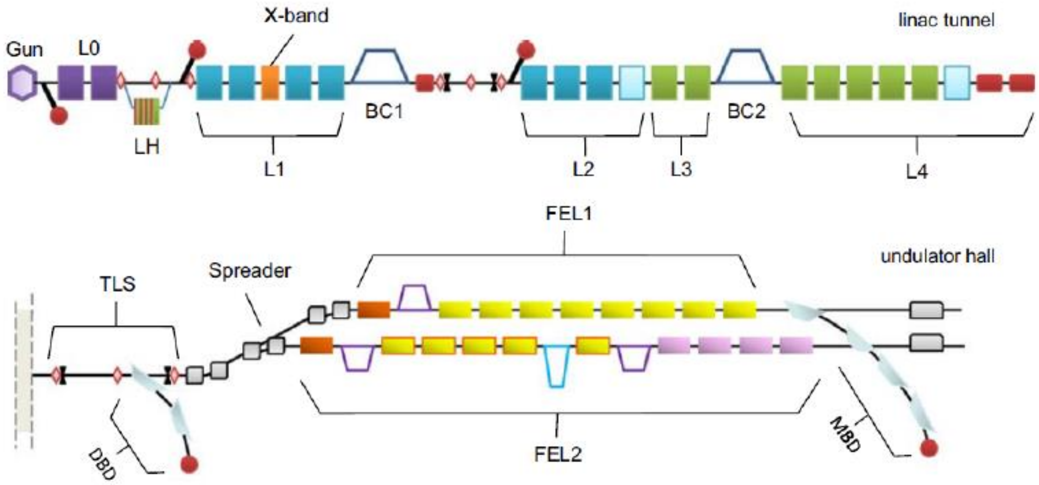
Elettra Sincrotrone Trieste

LAYOUT

- ❑ **FERMI Upgrade**
  - ❑ Beam energy upgrade
  - ❑ Beam quality upgrade
- ❑ FERMI linac
- ❑ High Gradient module
  - ❑ RF design
  - ❑ Fabrication & testing of short prototype
  - ❑ Fabrication & testing of full HG module
  - ❑ Installation of the HG module at FERMI linac
- ❑ Spherical Pulse Compressor
  - ❑ RF design
  - ❑ Fabrication and testing
- ❑ Summary and conclusions

The FERMI FEL

The **FERMI** linac-based FEL at the Elettra Laboratory (Trieste, IT) is an international user facility for scientific investigations in material science.
The electron bunches are produced in a laser-driven photo-injector and accelerated, with a **3-GHz, normal conducting Linac**, to energies up to **1.5 GeV**,



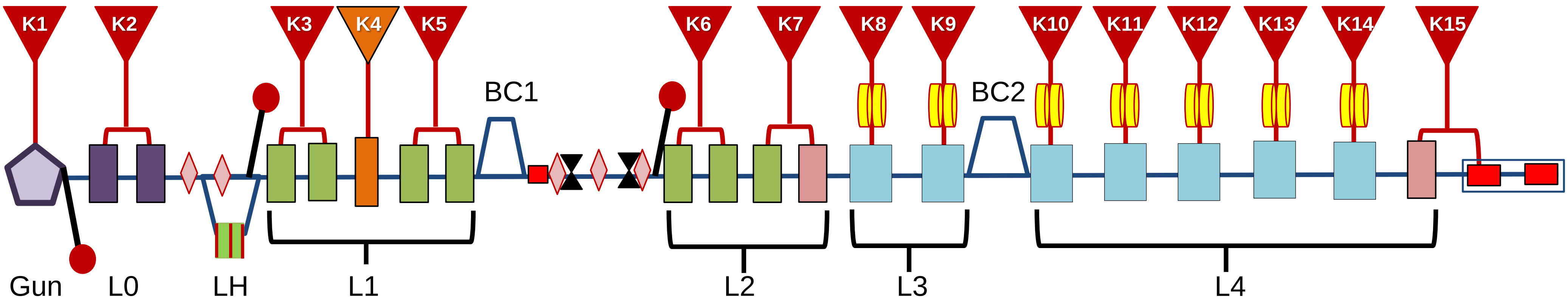
The FERMI facility comprises two separate coherent radiation sources, **FEL-1** and **FEL-2**.
FEL-1 operates in the wavelength range between **100 and 20 nm** via a single cascade harmonic generation, while the **FEL-2** is designed to operate at shorter wavelengths (**20-4 nm**) via a double cascade mechanism.

nuaman.shafqat@elettra.eu

Elettra Sincrotrone Trieste

THE FERMI LINAC (PRESENT)

The **FERMI Linac** is a S-Band (3 GHz), **1.5 GeV** normal conducting, linear accelerator.



Injector:

- 1 S-Band, RF Gun
- 2 S-Band, Forward TW structures

Linac 1 & Linac 2

- 8 S-Band, Forward TW Structures
- 1 X-Band, Linearizer

Linac 3 & Linac 4

- 7 S-Band, Backward TW Structures
- 1 S-Band, Forward TW structure

- **Power Sources**: 45 MW peak power, 4.5 µs pulse width, Klystron
- **Linac 1 & Linac 2**: one klystron feeds two FTW accelerating structures
- **Linac 3 & Linac 4**: one klystron feed one BTW accelerating structure

The FERMI Linac (Present) Acc. Sections Type

CERN Sections

- Developed as injector of LEP Injector Linac (LIL) in **1984**
- One **45 MW** klystron feeds two 4,5 m CERN sections.
- Accelerating gradient is **12,6 MV/m.**

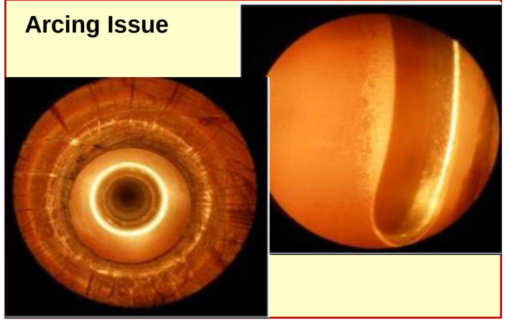
S0a and S0b Sections

- Came from the old Elettra injector.
- One **45 MW** klystron feeds two 3,2 m S sections.
- Accelerating gradient is **15,0 MV/m.**

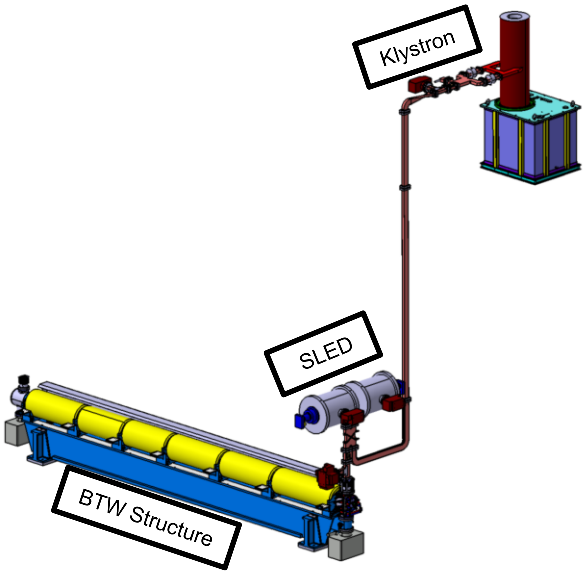
BTW Sections

- Came from old Elettra injector
- Each BTW section is fed by **45 MW** klystron followed by **SLED**.
- Limited to **18,0 MV/m at 50 Hz** due to breakdowns

Arcing Issue



Rusting Issue



	CERN sections	S0A-S0B	BTW sections
Mode	TW 2π/3	TW 2π/3	TW 2π/3
Frequency (MHZ)	2998,01	2998,01	2998,01
Length (m)	4,5	3,2	6,15
Filling time (µs)	1,5	0,903	0,757
Attenuation (Np)	0,7	0,603	0,611
Acc. Gradient (MV/m)	12,6	15,0	18,0
Energy gain (MeV)	56,7	48	120

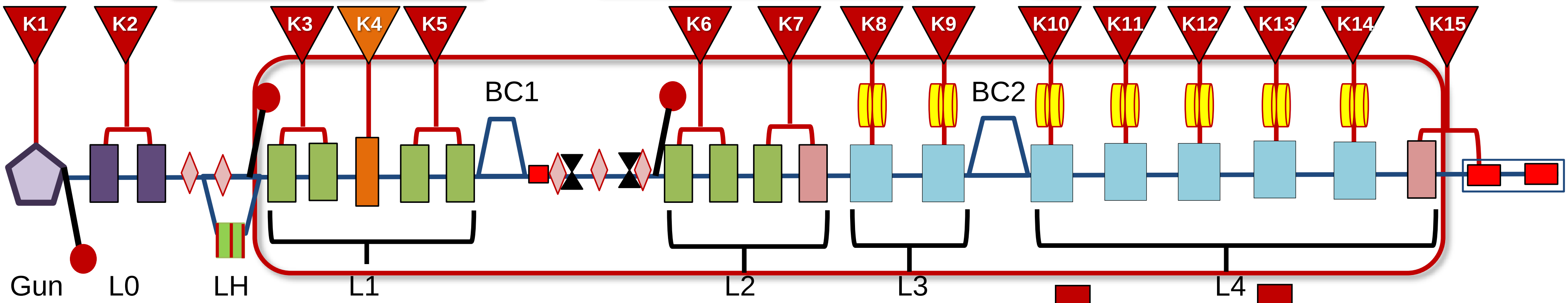
In order to reach a beam energy of **2.0 GeV**, all the BTW structures and the CERN sections will be pushed to higher gradient of 30 MV/m

nuaman.shafqat@elettra.eu

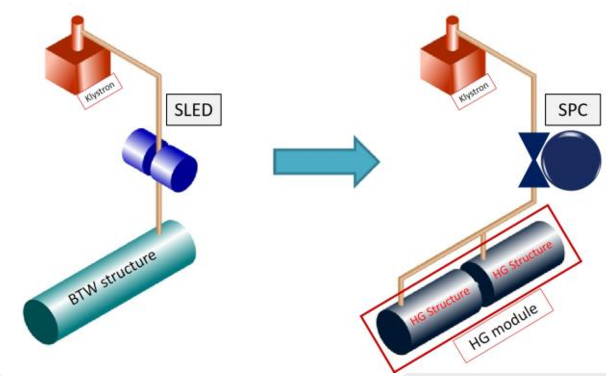
THE FERMI UPGRADE PROPOSAL

TO EXTEND THE RANGE TO SHORTHER WAVELENGTH UP TO 2 nm

Actual Linac Energy	Target Linac Energy	Solution
1.5 GeV @ 10Hz	**2.0 GeV @ 50Hz**	**High Gradient 30MV/m**



Replace 12 acc. sections + one deflector with 10 HG modules



Energy budget of the upgraded linac

Total Energy (MeV) = 2xRI + 4xCERN + 20xHG

Total Energy (MeV) = 2x50MeV + 4x57Mev + 20x90MeV

Total Energy (MeV) = 2128

It means we can operate HG sections at 28 MV/m

THE FERMI UPGRADE PROPOSAL

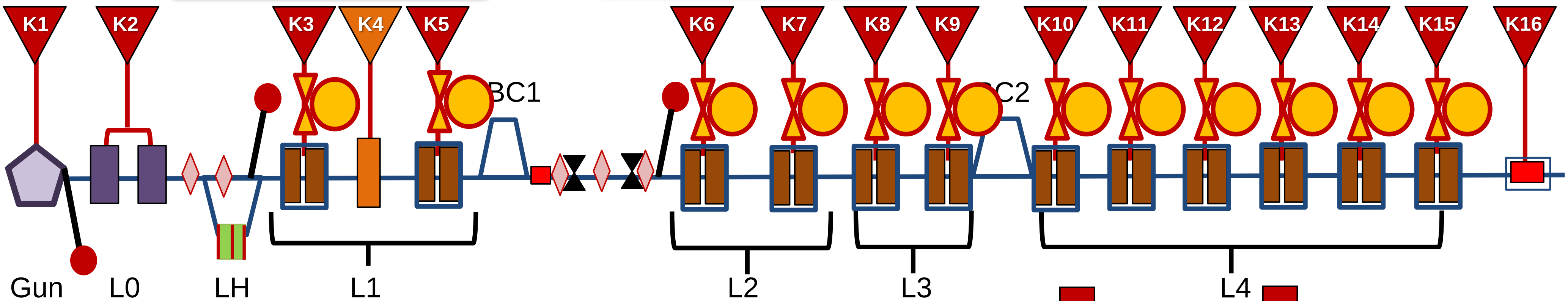
Elettra Sincrotrone Trieste

TO EXTEND THE RANGE TO SHORTHER WAVELENGTH UP TO 2 nm

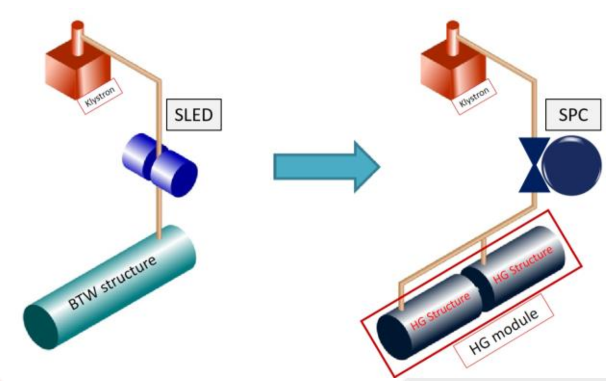
Actual Linac Energy
1.5 GeV @ 10Hz

Target Linac Energy
2.0 GeV @ 50Hz

Solution
High Gradient 30MV/m



Replace 12 acc. sections + one deflector with 10 HG modules



Energy budget of the upgraded linac

Total Energy (MeV) = 2xRI + 4xCERN + 20xHG

Total Energy (MeV) = 2x50MeV + 4x57Mev + 20x90MeV

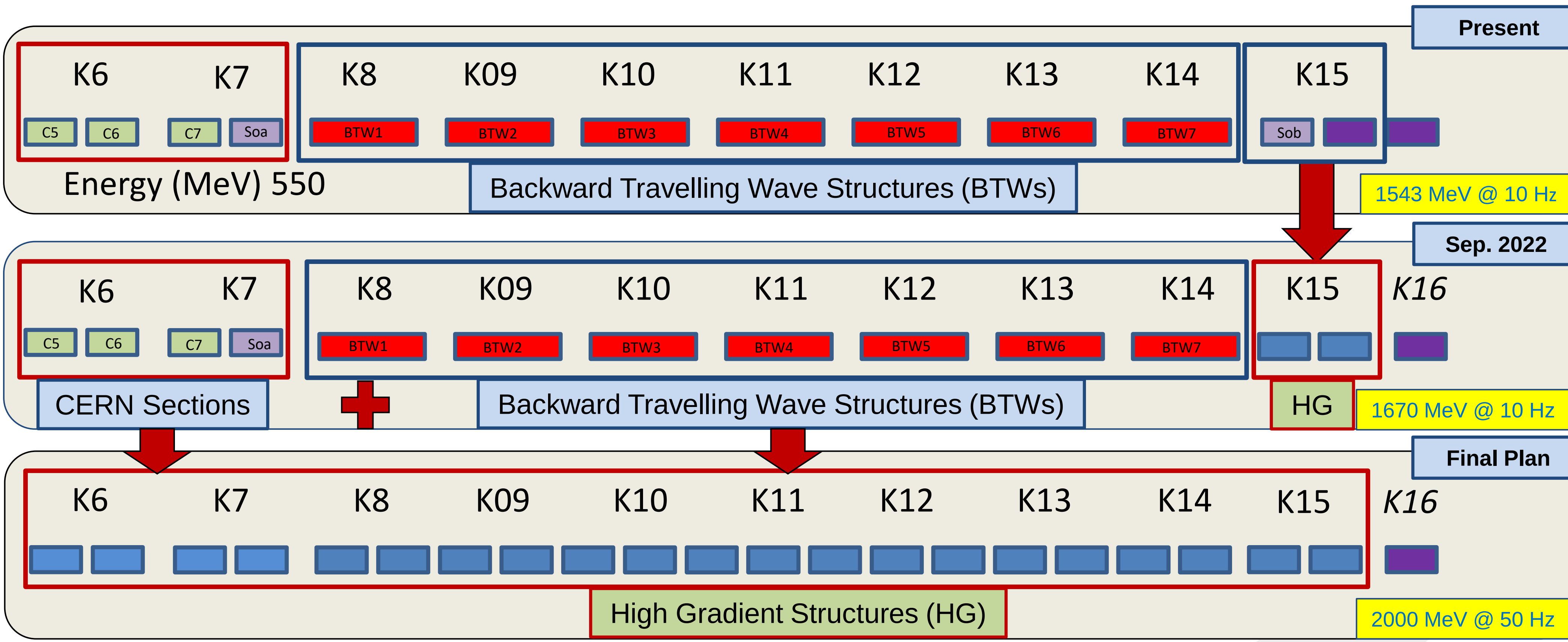
Total Energy (MeV) = 2128

It means we can operate HG sections at 28 MV/m

THE FERMI FEL UPGRADE PLAN
BEAM ENERGY UPGRADE

Elettra Sincrotrone Trieste

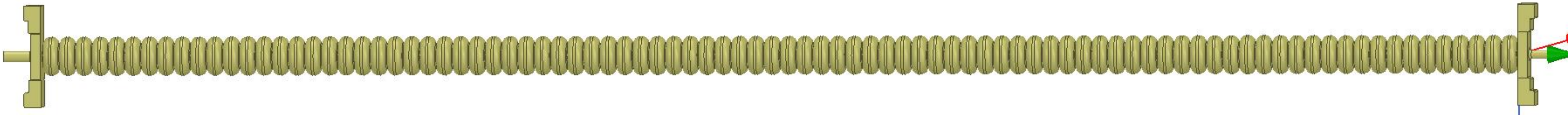
- ❑ **To reduce pulse duration to the sub-10 fs** range to resolve charge transfer processes, bond dynamics, vibrational dynamics
- ❑ **To extend photon energy range to N (410 eV), O (543 eV)** which translates to the extension of operating of FERMI to **~2 nm**.



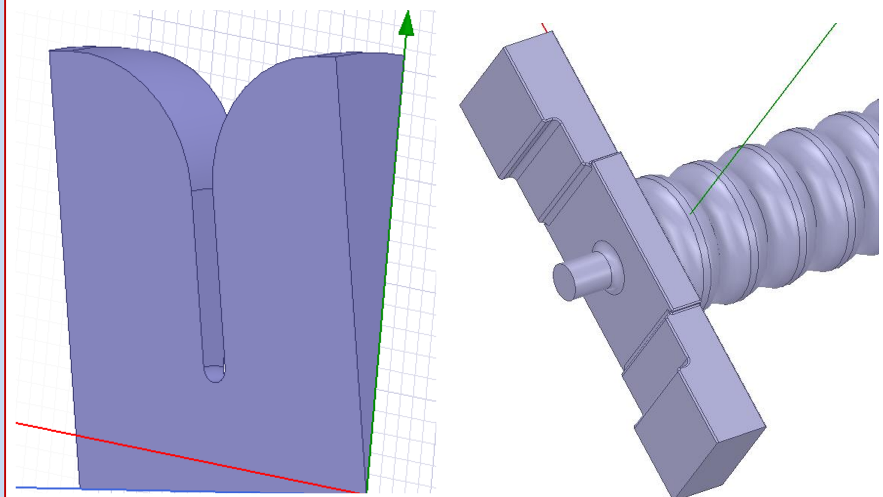
L. Giannessi., "FERMI Upgrade Perspectives" , in FUture of Seeded free Electron lasers. (FUSEE), Trieste, Italy, 10 Nov. 2019

nuaman.shafqat@elettra.eu

NEW ACCELERATING MODULE RF DESIGN

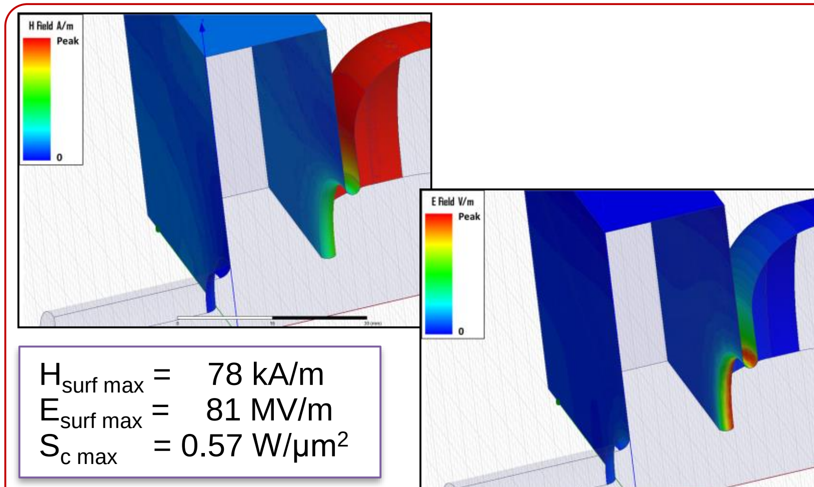


- The new accelerating module will be comprised of 3.0 m long, **constant gradient type** structures. **Double rounding** is introduced to reduce Ohmic losses and increase Q
- A customized version of **dual-fed-electric coupled (EC) coupler** is chosen for the new high gradient (HG) structures
  - Very low surface magnetic field
  - Easy to machine
  - Reduced cost of fabrication



Structure RF Parameters		
L	2988.3	mm
N_{cell}	84	
a	11.13 → 8.8	mm
R_{sh}	72.07 → 80.70	MΩ/m
Q_0	15850	
Filling Time	644.8	ns
Attenuation	0.383	Neper

Coupler RF Parameters		
	Input Coupler	Output Coupler
E_{surf} [MV/m]	78	82
H_{surf} [kA/m]	69	71
S_c [MW/mm^2]	0,47	0,39
k_q [V/ms]	1956	1319



$H_{surf\ max}$ = 78 kA/m
$E_{surf\ max}$ = 81 MV/m
$S_{c\ max}$ = 0.57 W/μm^2

RF design was concluded in August 2019

nuaman.shafqat@elettra.eu

C. Serpico, N. Shafqat, A. Grudiev, and R. Vescovo, "High gradient high reliability, and low wakefields accelerating structures for the FERMI FEL", *Review of Scientific Instruments*, vol. 88, p. 073303, 2017
N. Shafqat, S. Di Mitri, C. Serpico, and S. Nicastro, "Design study of high gradient, low impedance accelerating structures for the FRRMI free electron laser upgrade", *Nuclear Instruments and Methods in Physics Research A*, vol. 867, pp. 78-87, 2017

THE SHORT PROTOTYPE LOW POWER MEASUREMENTS

Elettra Sincrotrone Trieste

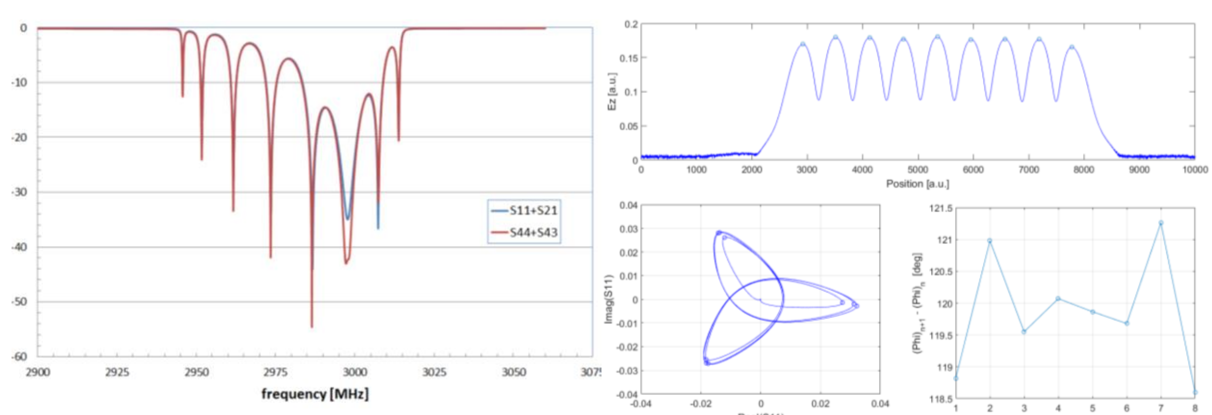
HG2023

- To prove the reliability and feasibility of the upgrade plan, a short prototype was built in collaboration with Paul Scherrer Institute (PSI).
- The prototype is realized using the same structure technology as developed for SwissFEL
- The prototype is made by 7 regular cells & 2 EC-couplers.

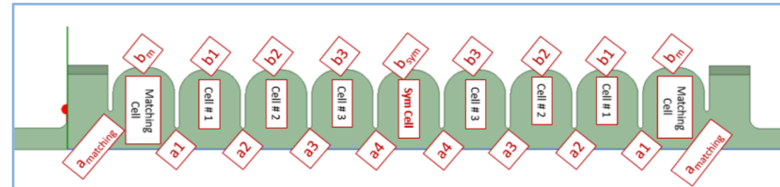
Structure RF Parameters		
L	353.332	mm
$N_{cell(regular)}$	7	
$N_{cell(coupler)}$	2	
a	11.13 → 8.8	mm
b	41.61 → 41.60	
R_{sh}	71.14 → 71.38	MΩ/m
Q_0	≈15850	
Filling Time	≈50	ns
E_s	81 → 85	MV/m
H_s	71 → 74	kA/m

RF measurements and bead-pull test

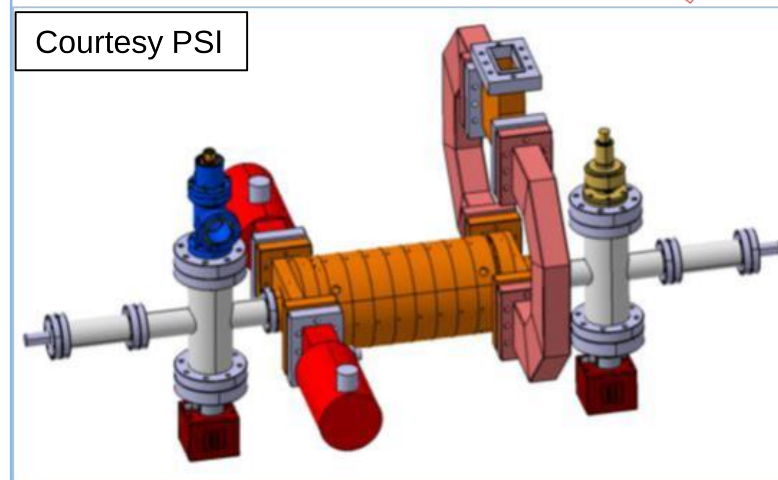
Courtesy PSI



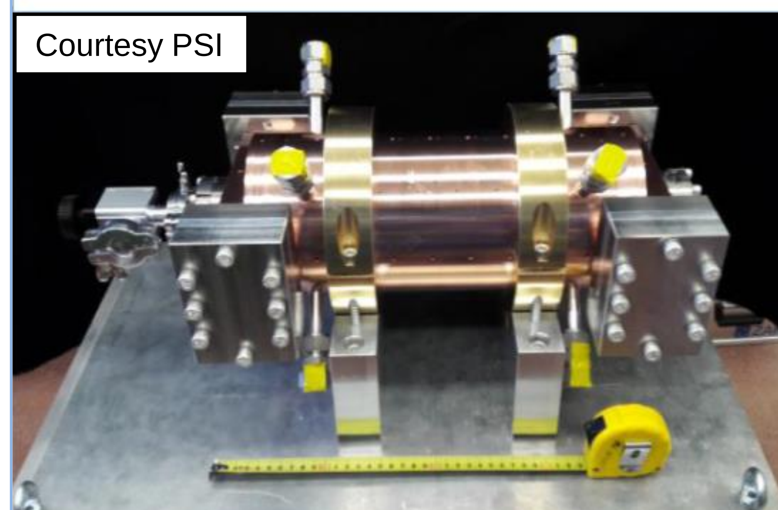
Short HG Prototype



Courtesy PSI



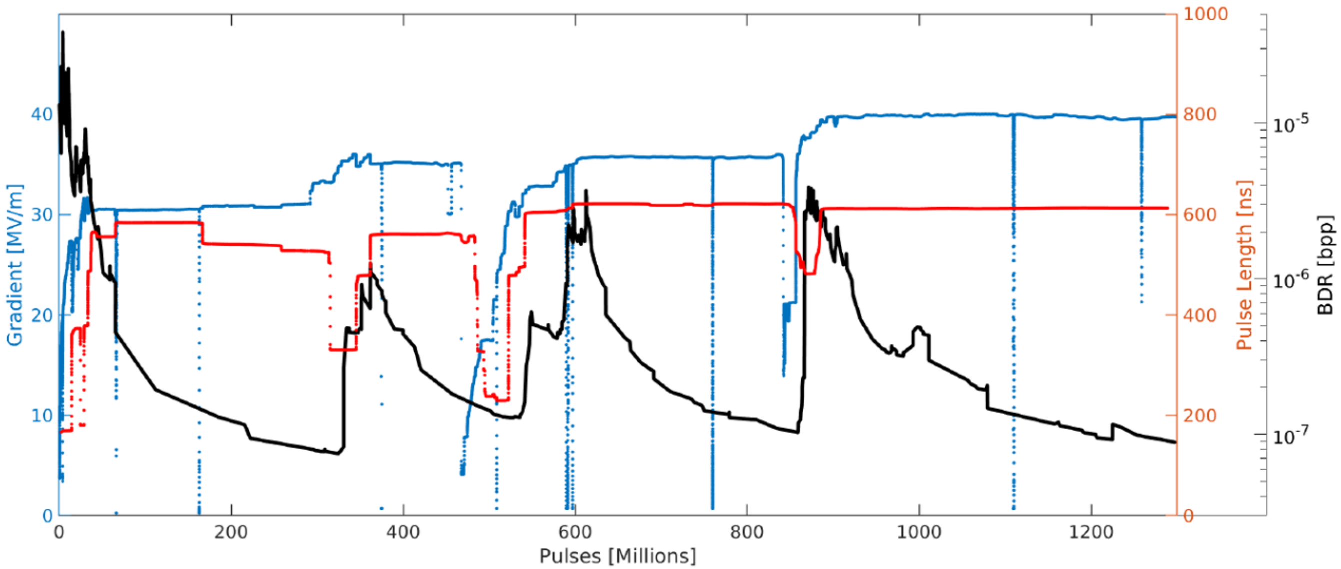
Courtesy PSI



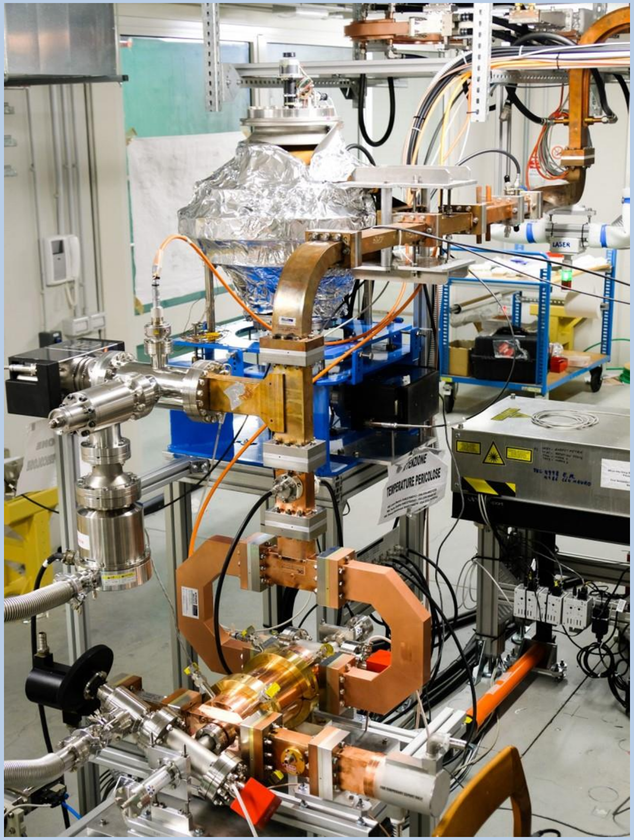
U. Ellenberger et al., "Status of the Manufacturing Process for the SwissFEL C-Band Accelerating Structures" , in *Proc. 35th Int. Free Electron Laser Conf. (FEL'13)*, New York, NY, USA, Aug. 2013, paper TUPSO17 , pp. 245-249.

The Short Prototype Complete Conditioning History

Acc. Gradient (MV/m)	PWR @ Ptype (MW)	Start Date	End Date	# of Pulses (Million)	BDR (bpp)
30	72	01-06-2018	07-11-2018	225	2.0×10^{-8}
35	98	30-01-2019	21-05-2019	229	7.3×10^{-8}
39	122	31-08-2019	19-12-2019	400	7.9×10^{-8}

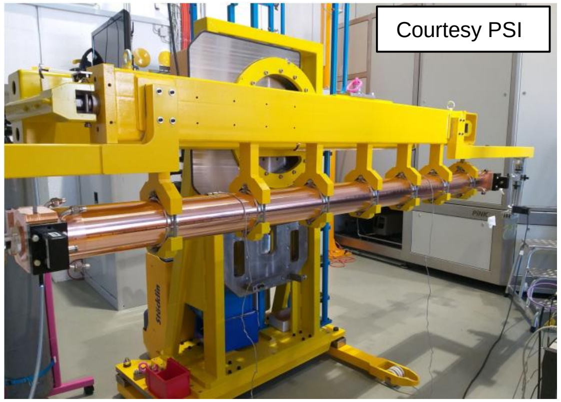


During the **Spring Shutdown (April 2018)** the prototype was installed in FERMI Test Facility.

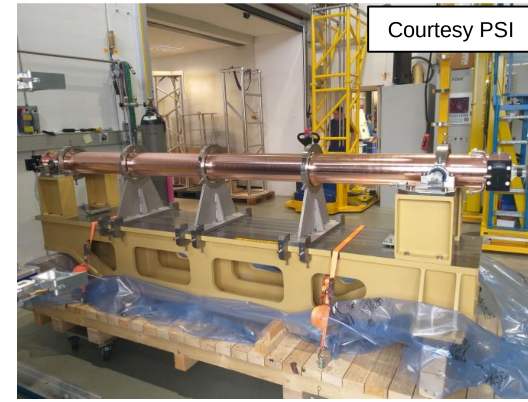


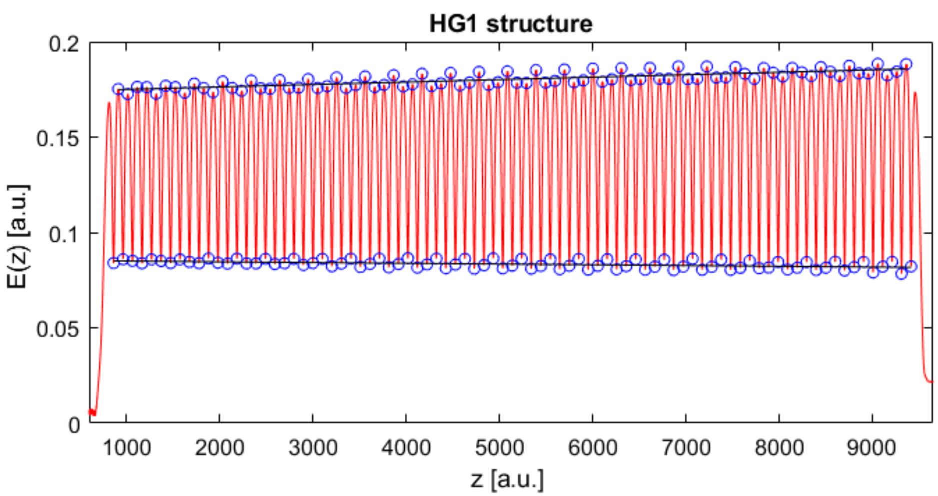
N. Shafqat et al., "Design and high-power test of a short prototype of high gradient S-band accelerating structure for the FERMI free electron laser linac upgrade")", *Nuclear Instruments and Methods in Physics Research A*, vol. 979, Nov. 2020

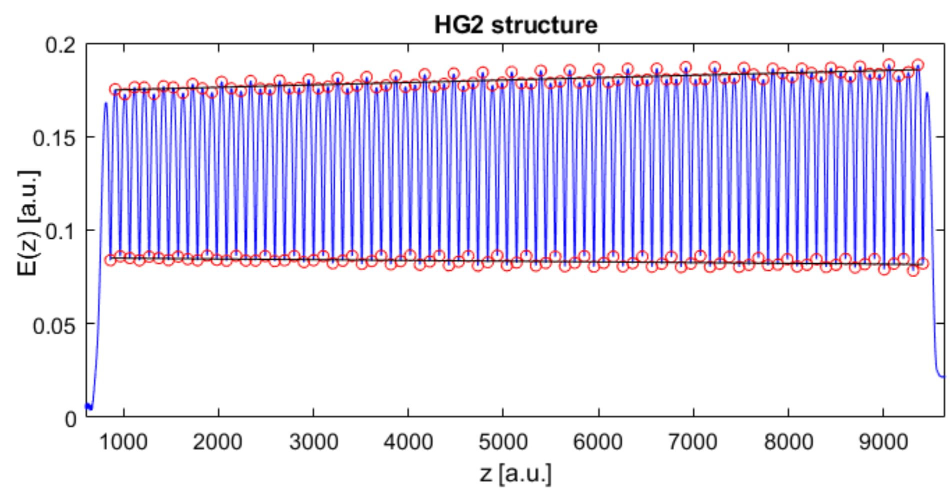
The First HG Module Low Power Measurements

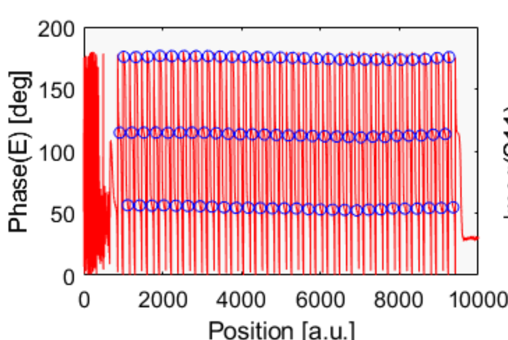


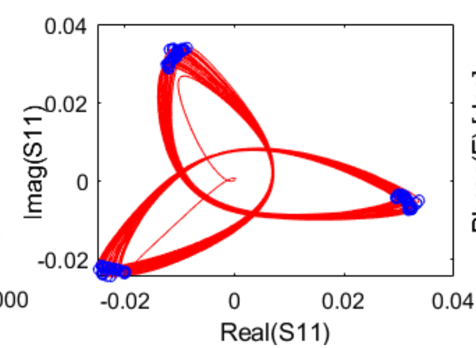
- ❑ Low power measurements of the HG module were performed at PSI.
- ❑ Operating temperatures were
  - ❑ HG1 34.6 ^{o}C
  - ❑ HG2 33.8 ^{o}C

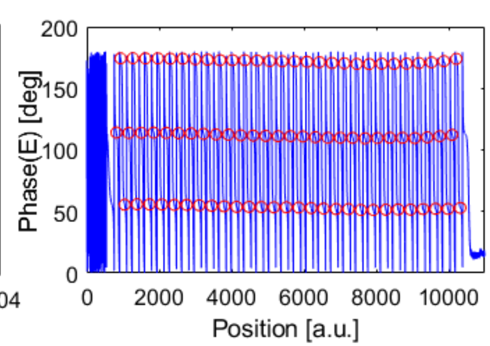


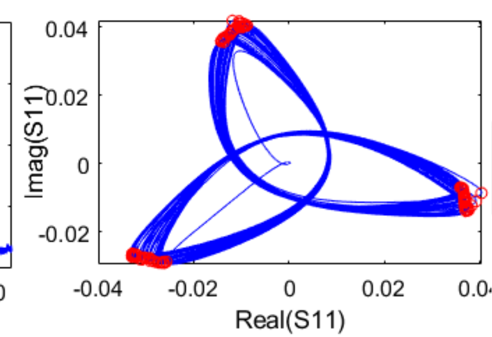








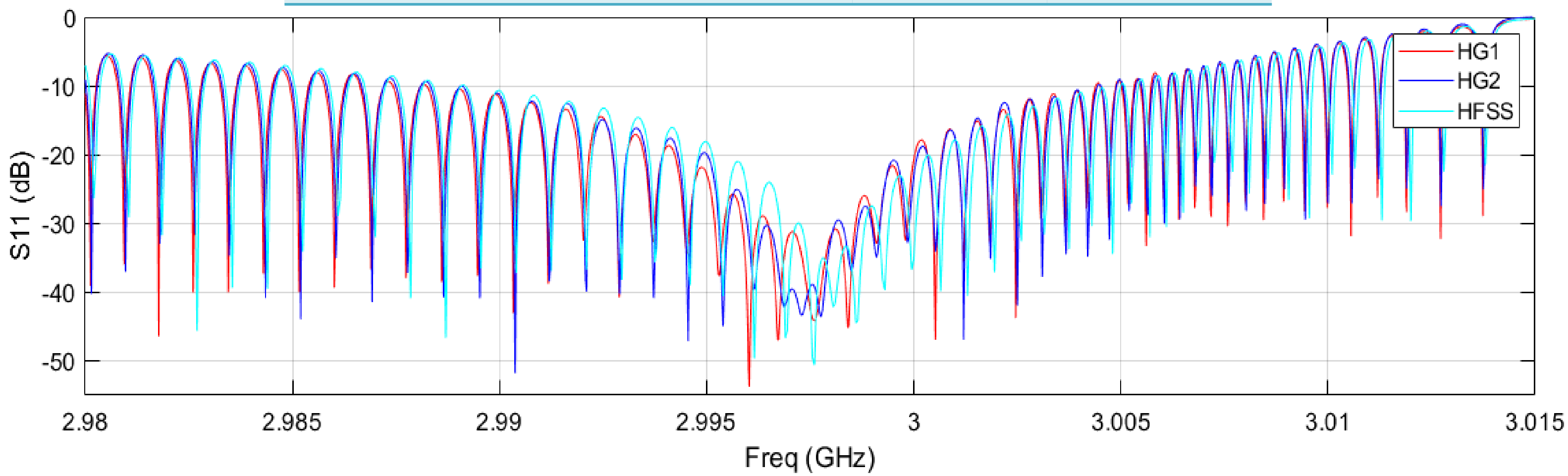


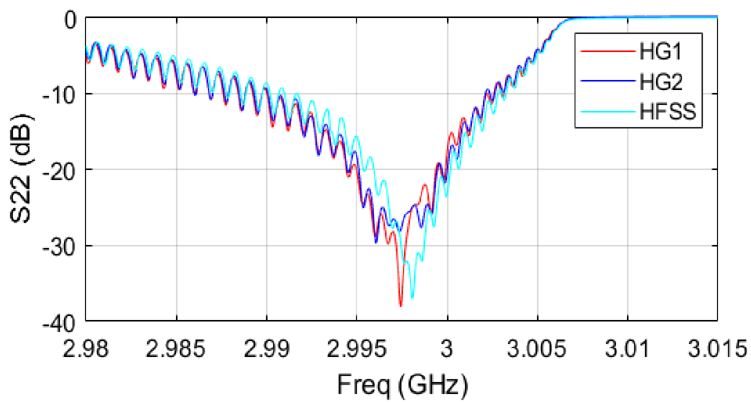


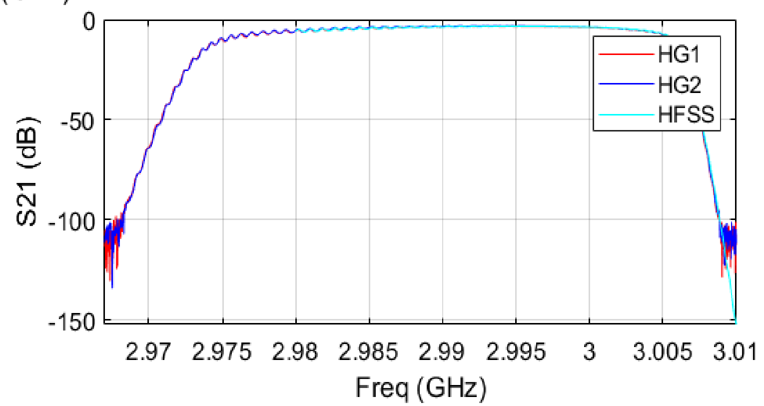
nuaman.shafqat@elettra.eu

The First HG Module Low Power Measurements

	HFSS	HG1	HG2
Operating temperature	35 ^{o}C	34.6 ^{o}C	33.8 ^{o}C
S11 (dB)	-38	-32	-33
S21 (dB)	-3.44	-3.55	-3.37
S22 (dB)	-35	-25.7	-25.3

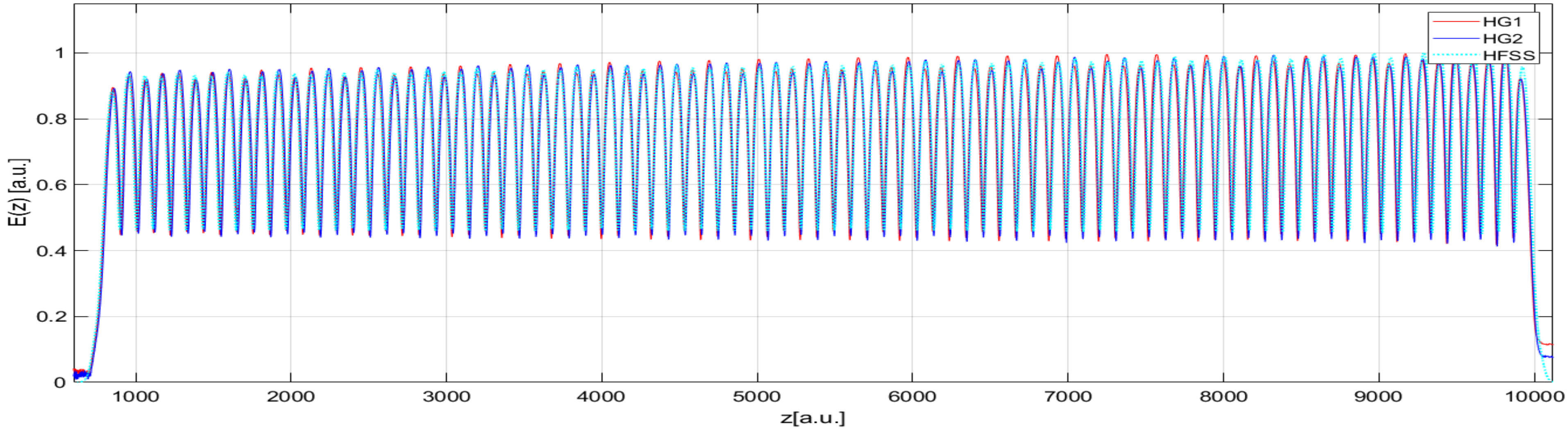


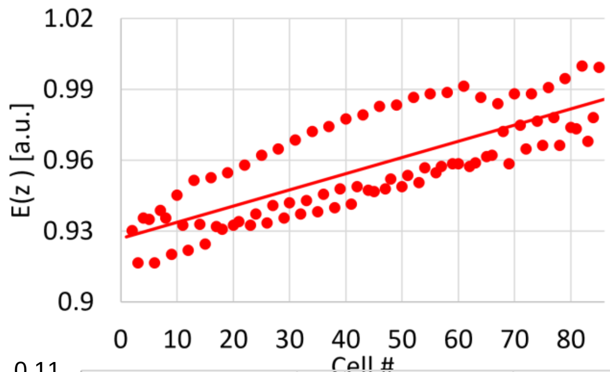


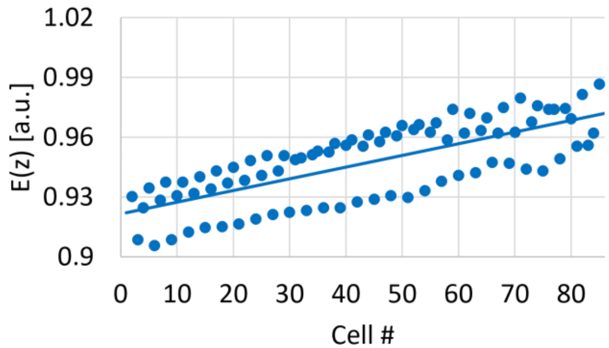


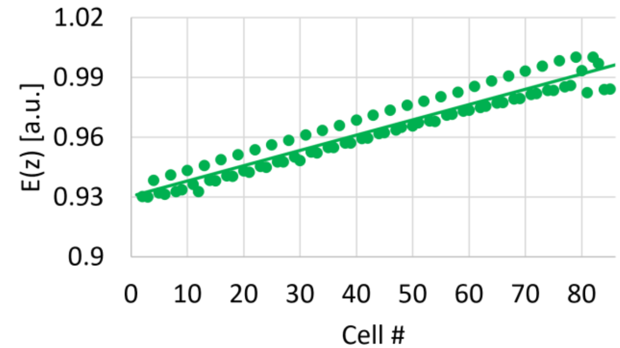
nuaman.shafqat@elettra.eu

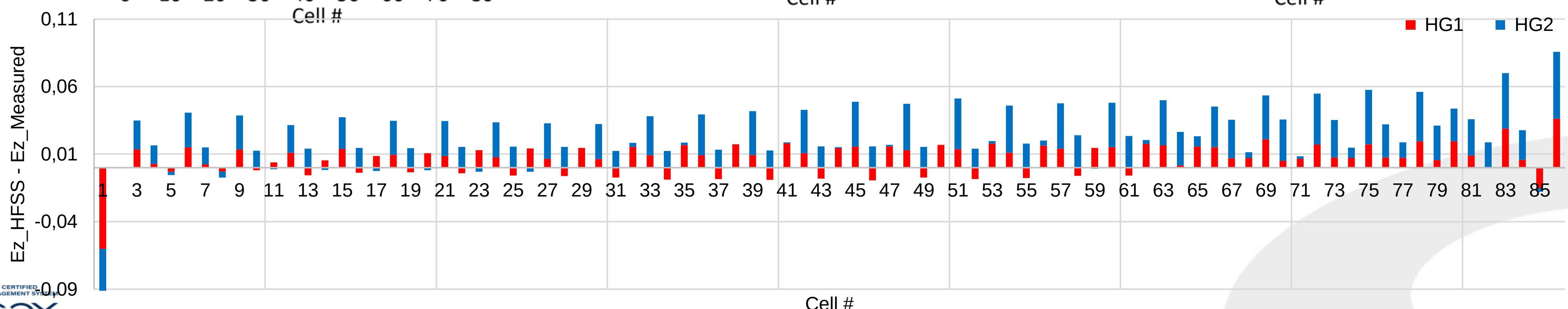
THE FIRST HG MODULE
LOW POWER MEASUREMENTS







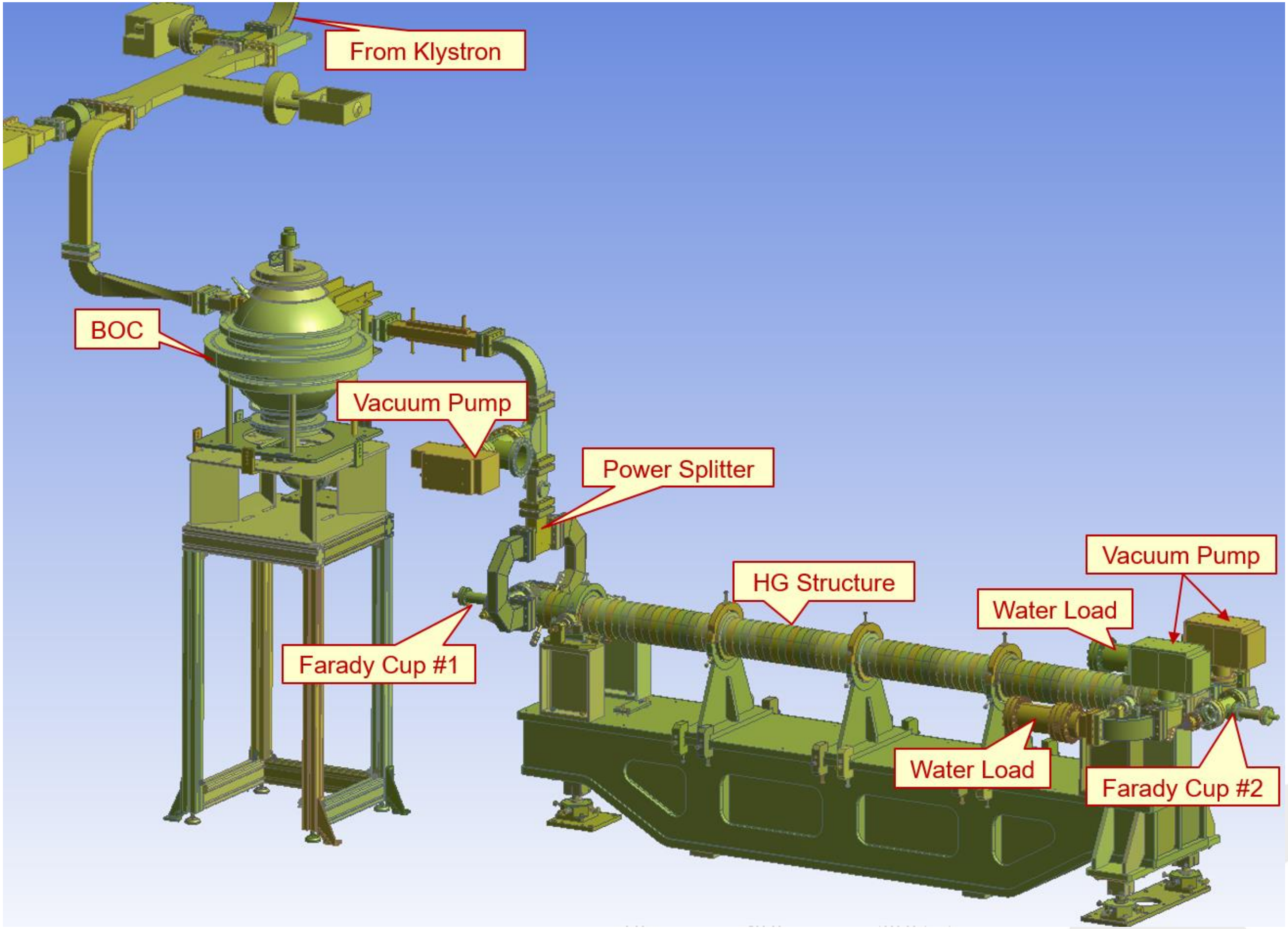




nuaman.shafqat@elettra.eu

N. Shafqat, et al, “Fabrication, conditioning and installation of the 1st high gradient S-band accelerating module for the energy upgrade of the FERMI free electron laser linac”, *Nuclear Instruments and Methods in Physics Research A*,1055 (2023) 168543

THE FIRST HG MODULE CONDITIONING (HG1)



THE FIRST HG MODULE CONDITIONING SETUP (HG1)

Phase I (conditioning)

- Rep. Rate: 50 Hz
- Start Date: 28-04-2022
- End Date: 17-05-2022
- Level Achieved:
  - Pulse Width:350 ns
  - Power Level:72 MW
  - # of pulses [million]: 80

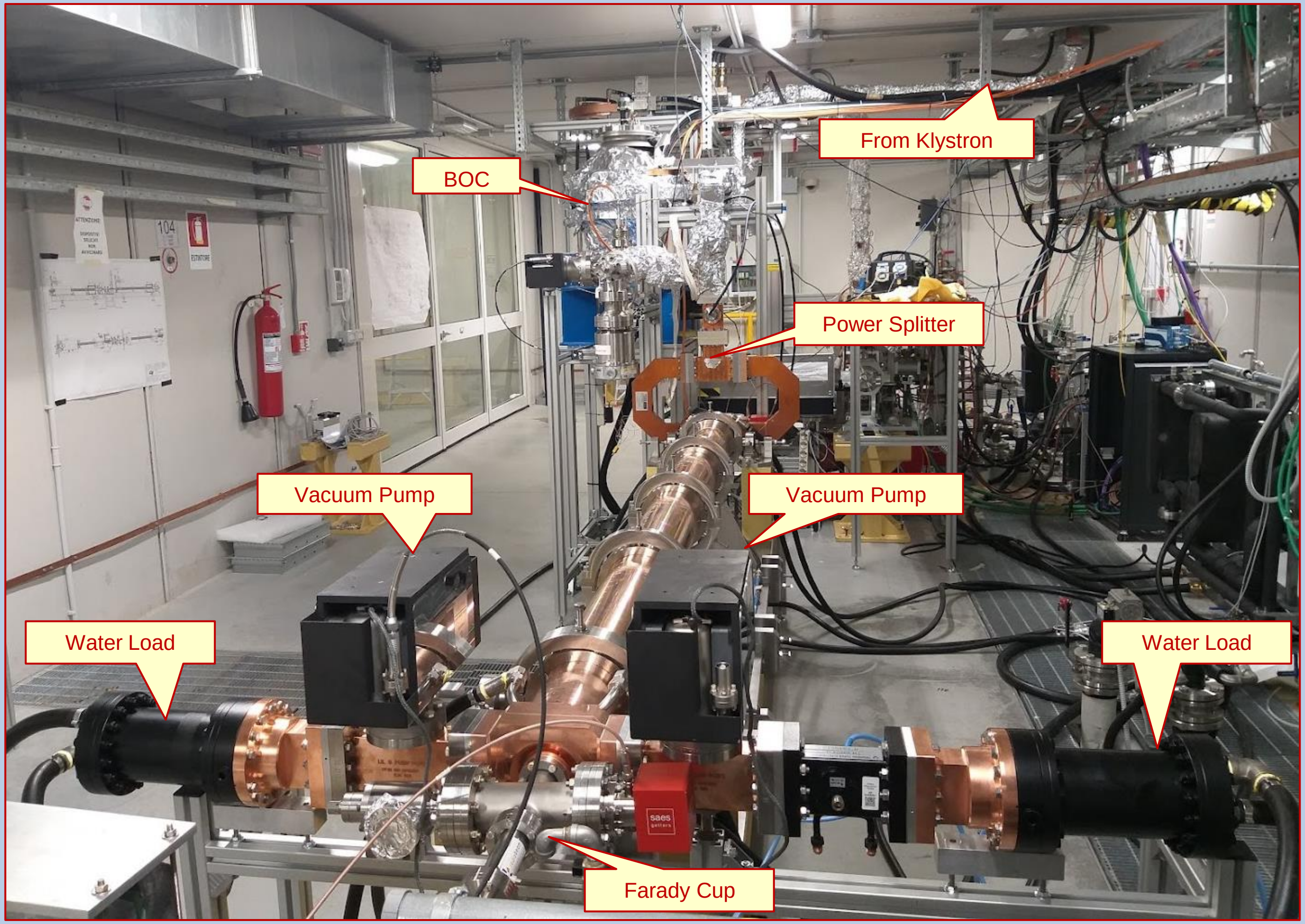
Phase II (conditioning)

- Rep. Rate: 50 Hz
- Start Date: 17-05-2022
- End Date: 11-06-2022
- Level Achieved:
  - Pulse Width:700 ns
  - Power Level:72 MW
  - # of pulses [million]: 100

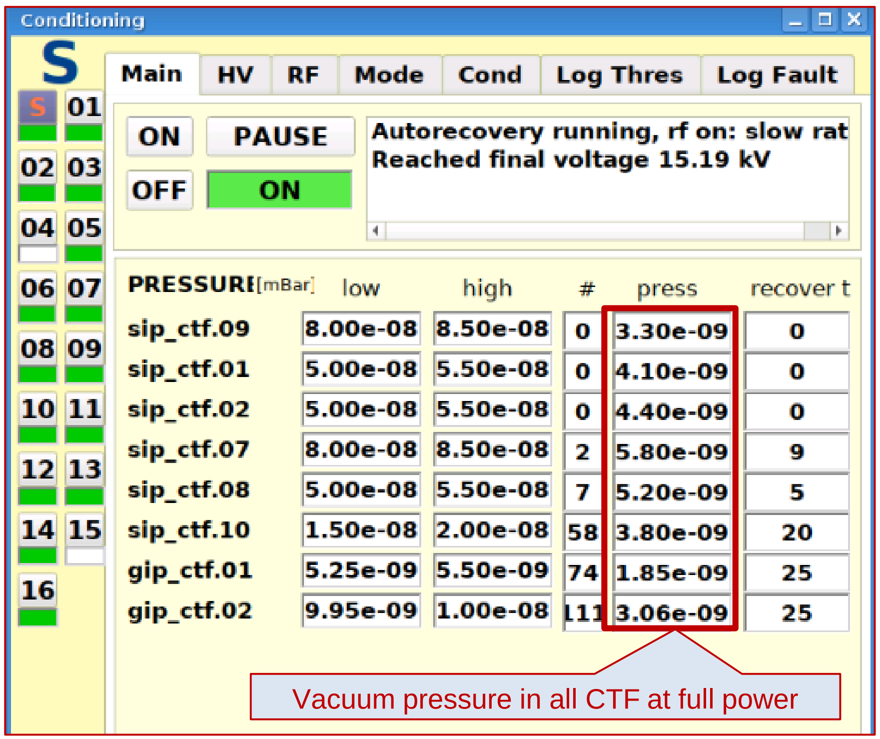
Phase III (constant power op.)

- Rep. Rate: 50 Hz
- Start Date: 11-06-2022
- End Date: 25-07-2022
- Operating level:
  - Pulse Width:700 ns
  - Power Level:75 MW
  - # of pulses [million]: 180

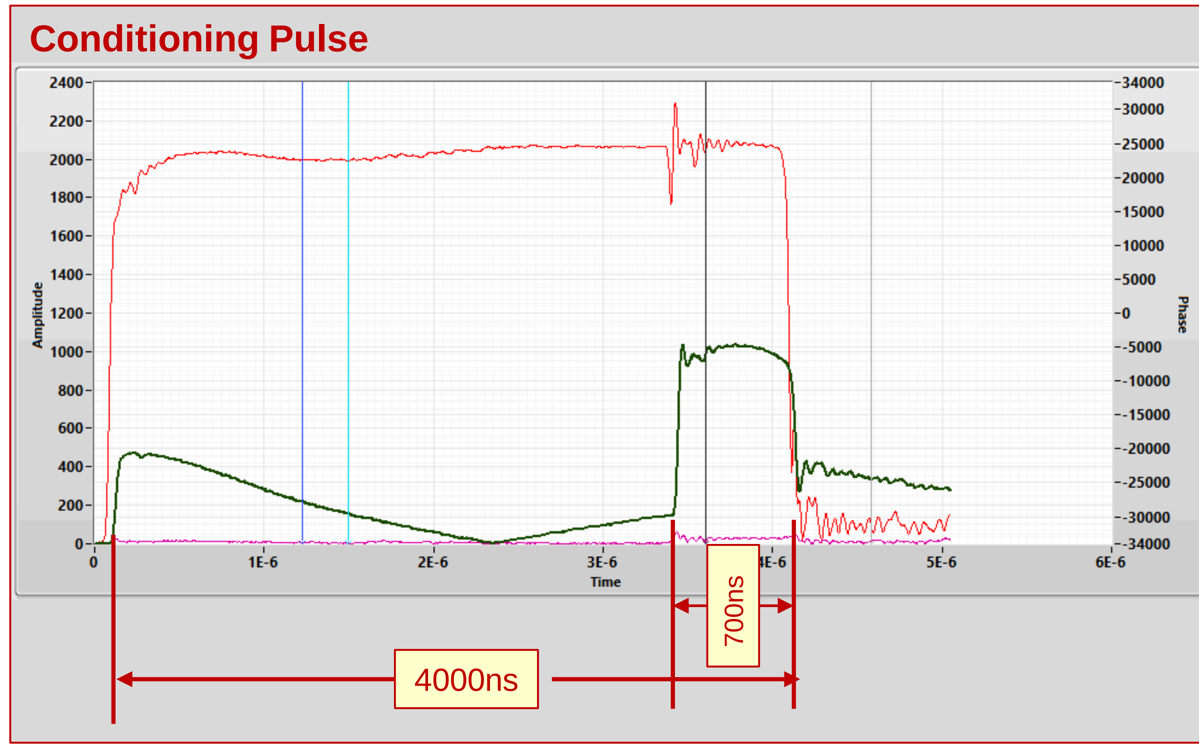
During the **Spring Shutdown (April 2022)** the HG structure was installed in FERMI Test Facility.



The First HG Module Conditioning (HG1)

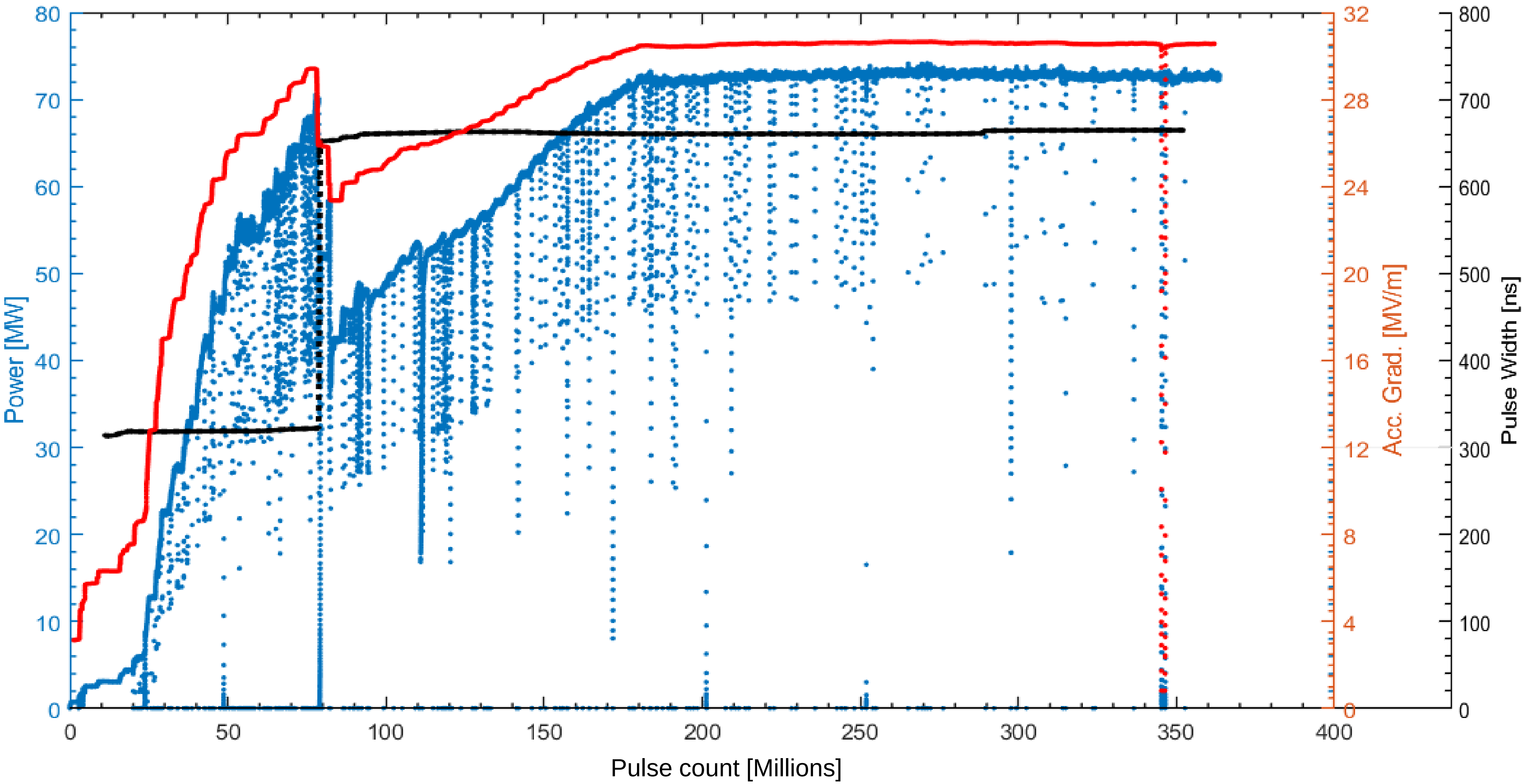


Conditioning Pulse



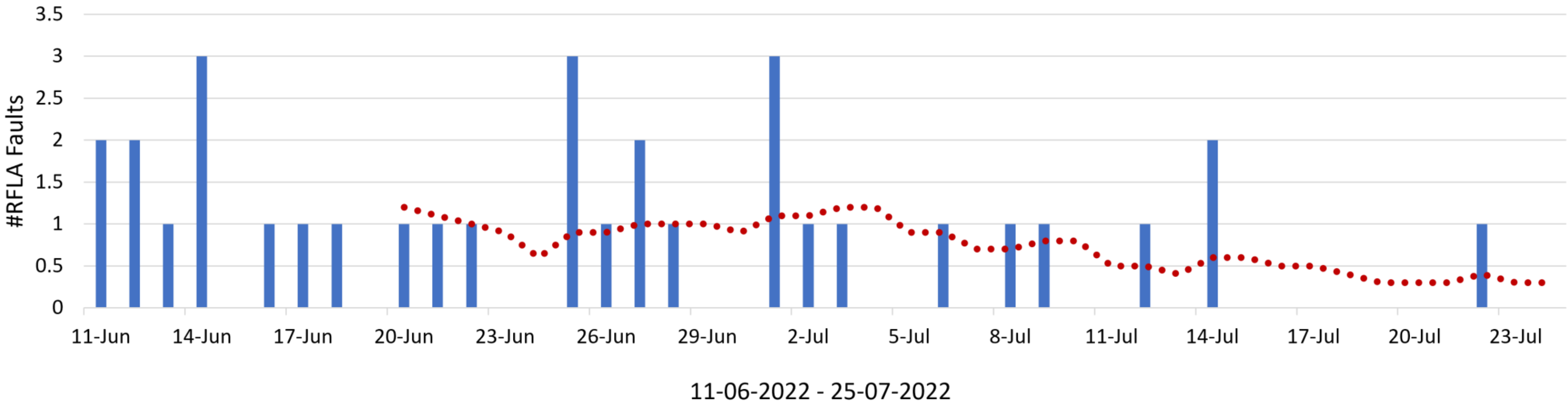
Elettra Sincrotrone Trieste

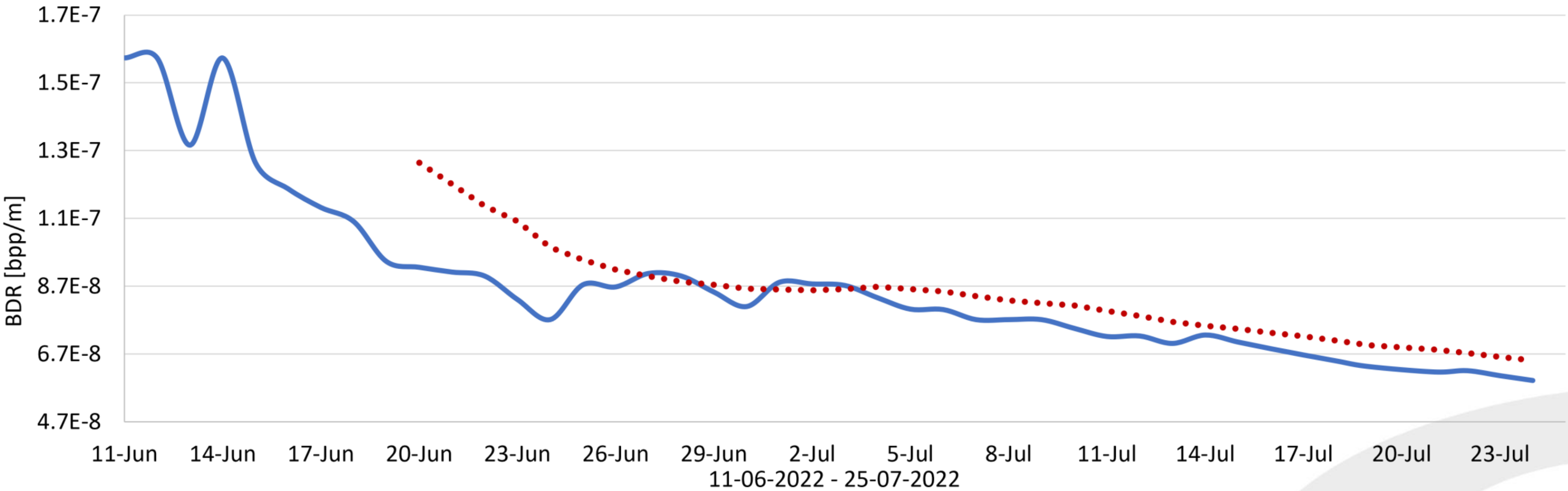
The First HG Structure History Plot (HG1)



nuaman.shafqat@elettra.eu

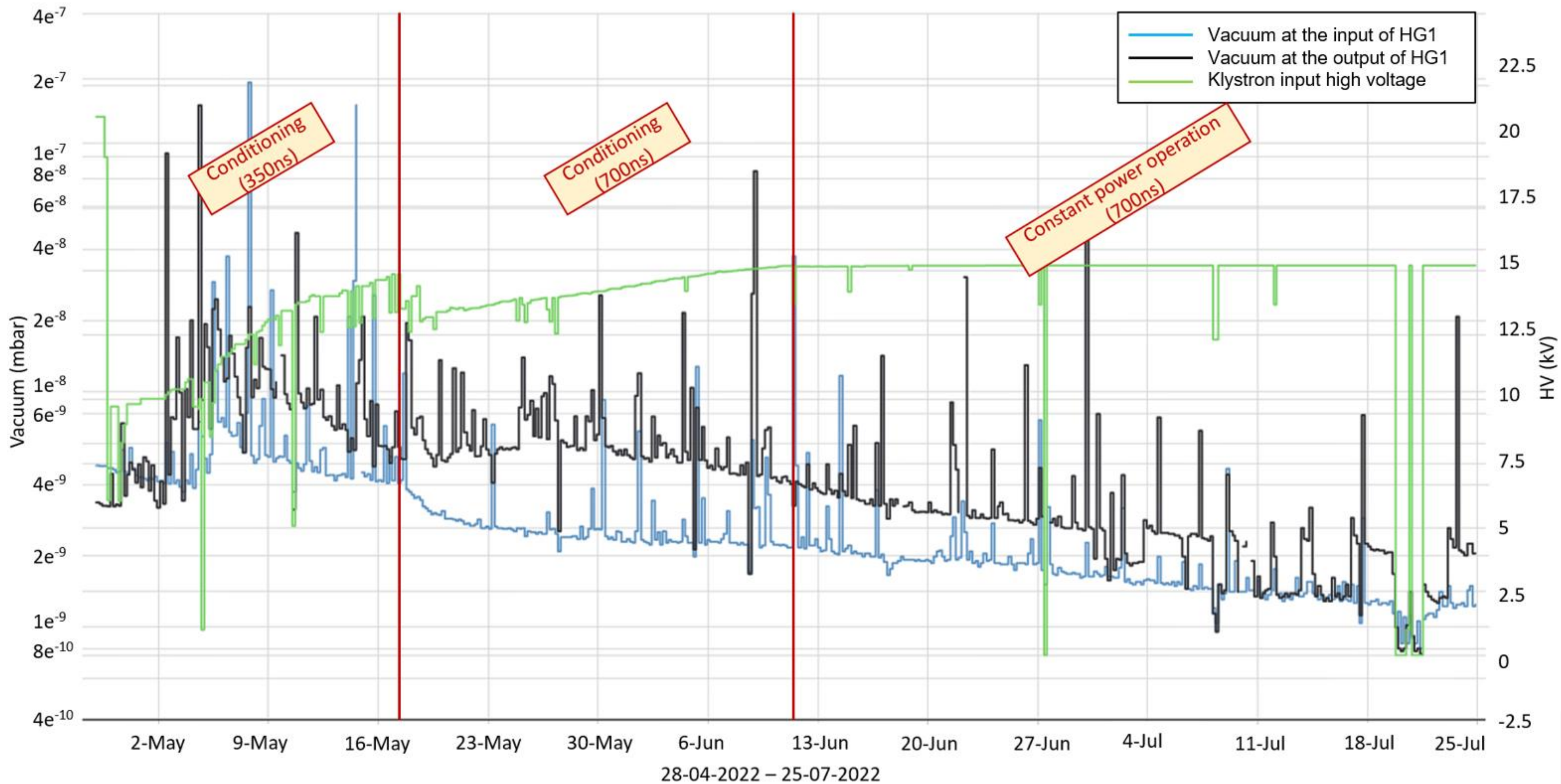
The First HG Structure Estimated BDR (HG1)



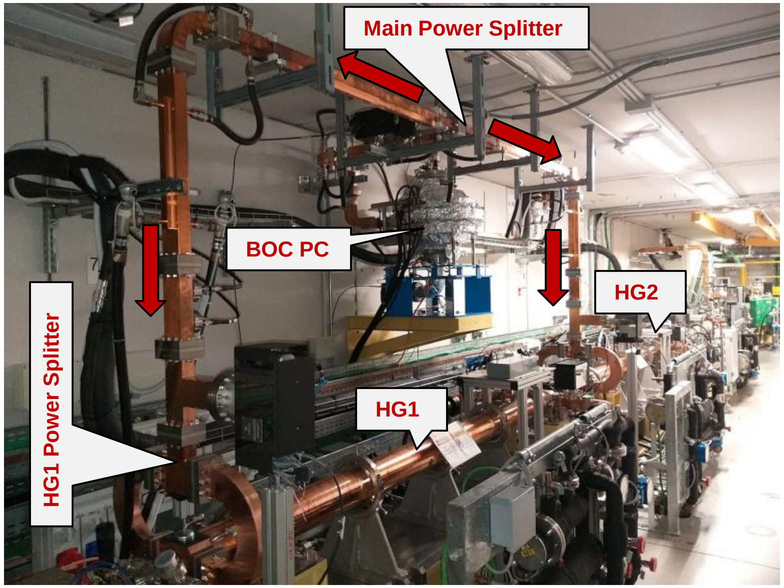


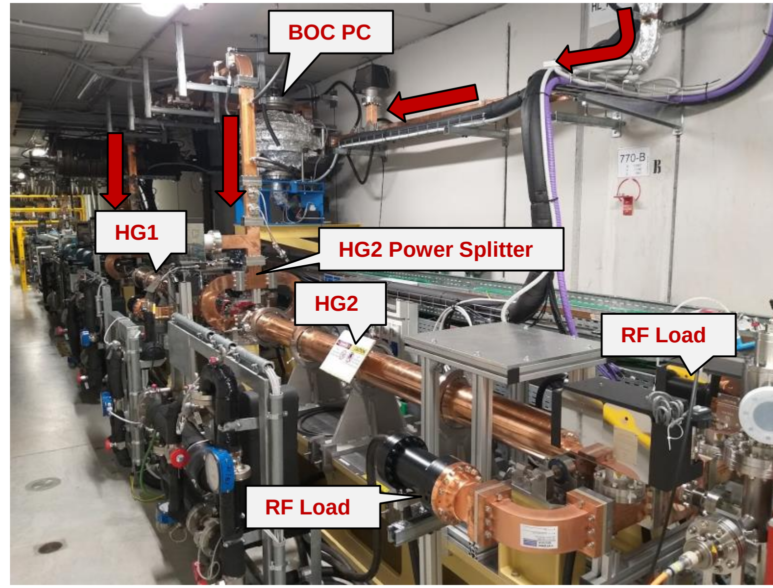
Elettra Sincrotrone Trieste

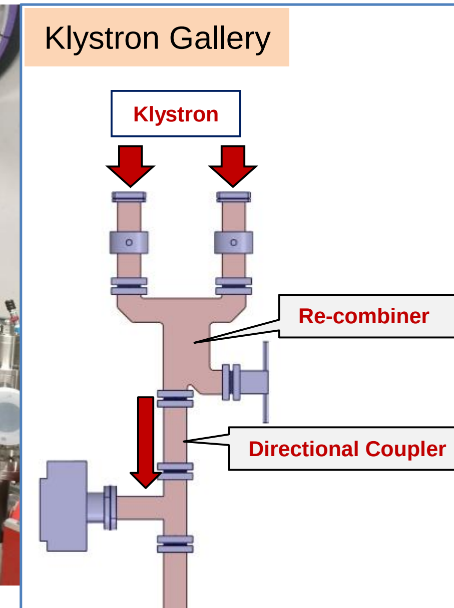
THE FIRST HG MODULE VACUUM (HG1)

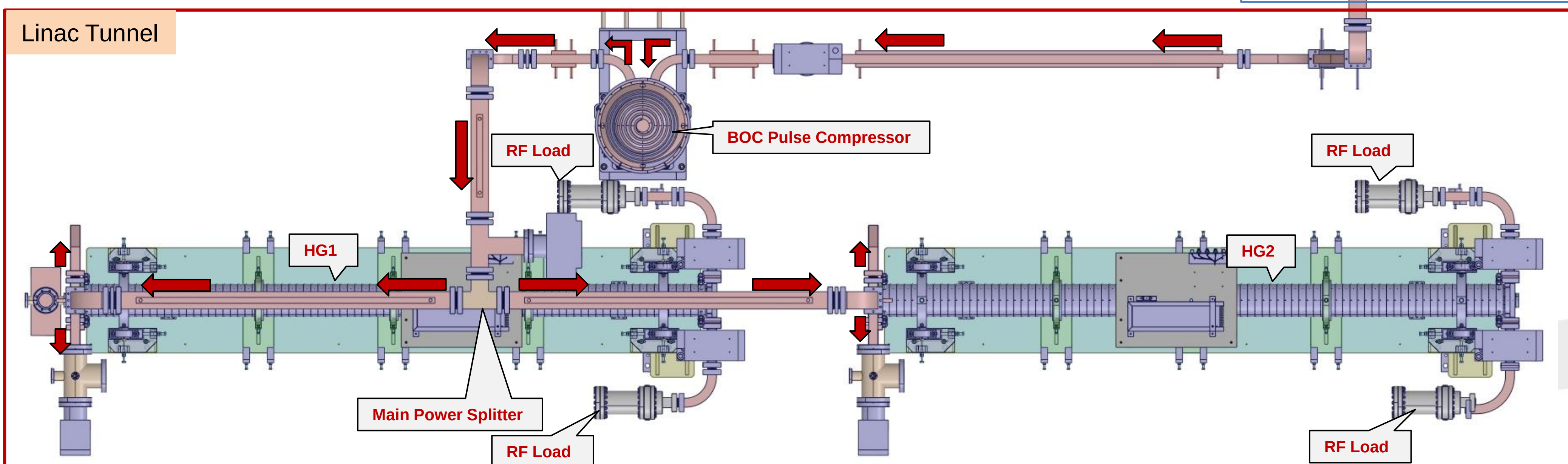


The First HG Module Installation in the FERMI Tunnel

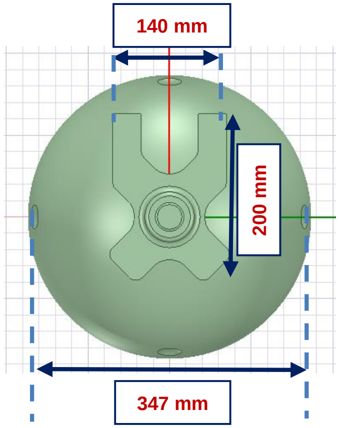


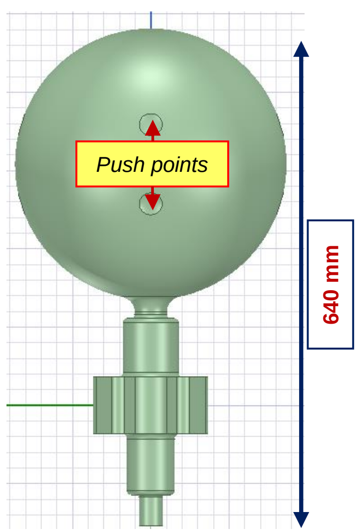


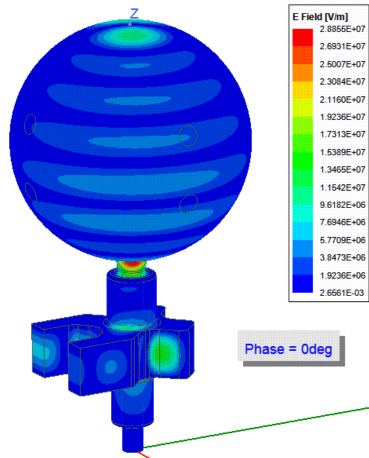


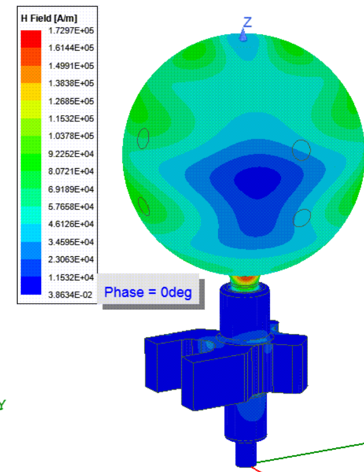


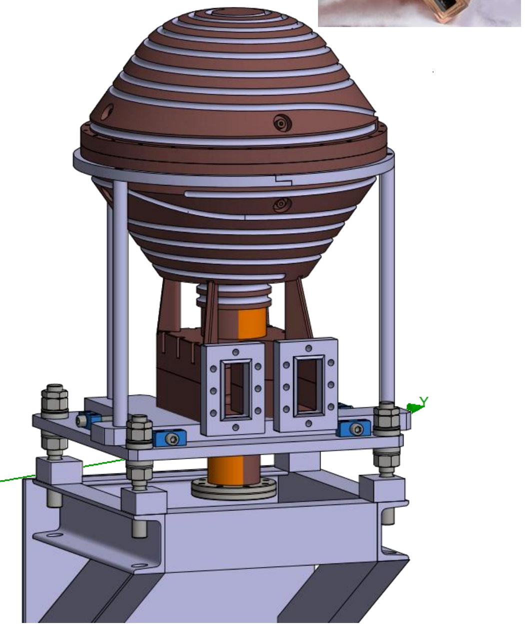
The Spherical Pulse Compressor RF Design



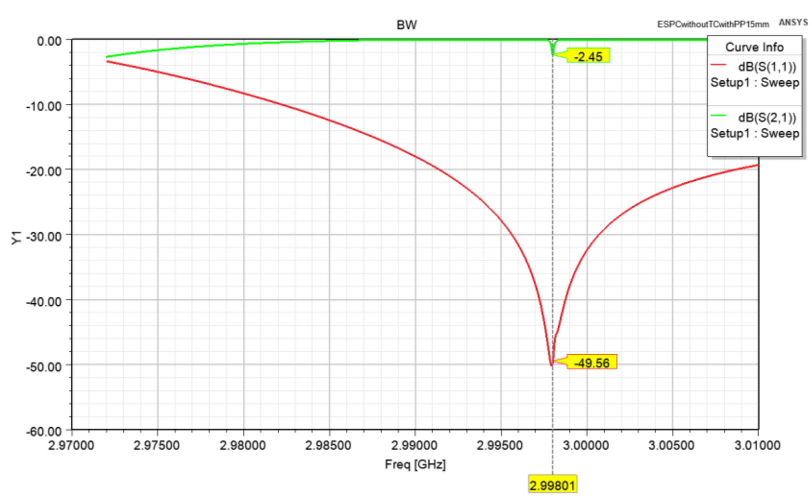








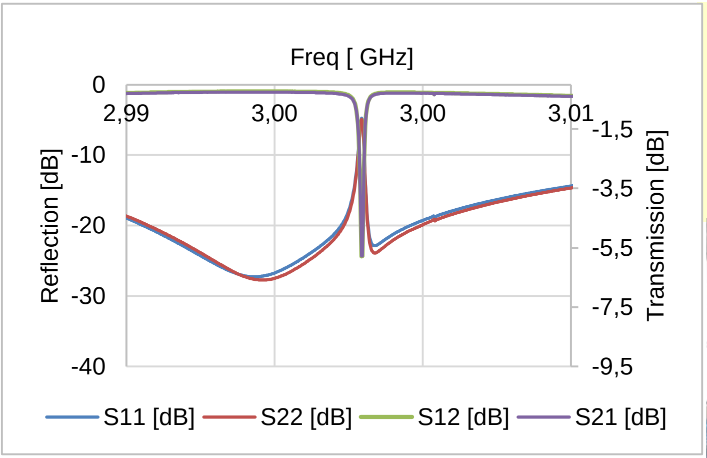
RF Parameters		
f_0	2.99801	GHz
Nominal Temperature	35	^oC
Mode	TM13	
Q0	≈140000	
Coupling Coefficient	7.2±0.1	
E @ 45 MW	28.16	MV/m
H @ 45 MW	169.75	kA/m



nuaman.shafqat@elettra.eu

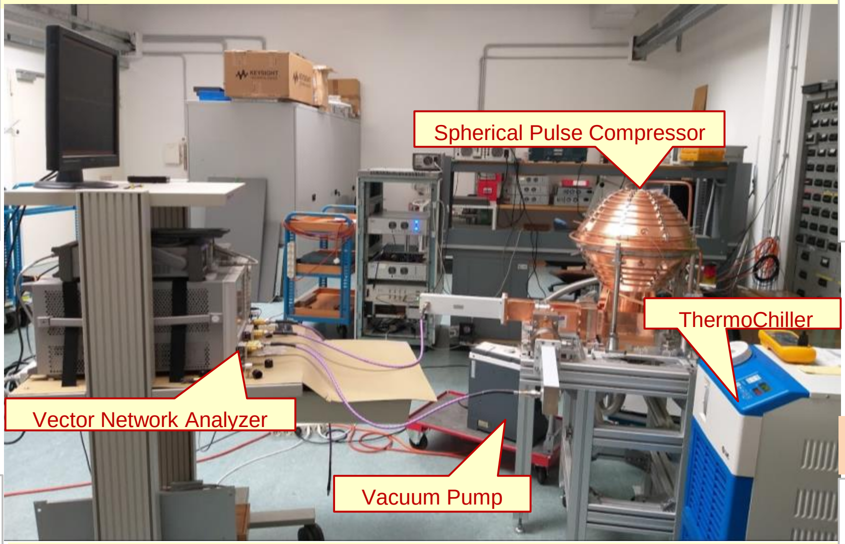
The Spherical Pulse Compressor Low Power Mesurements

Before Tuning



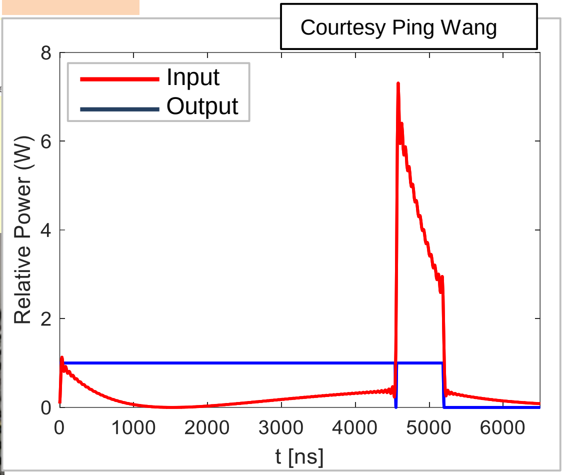
Measurement Setup

- Water Temperature: 33,4 C
- Coupling frequency: 2998,01 MHz

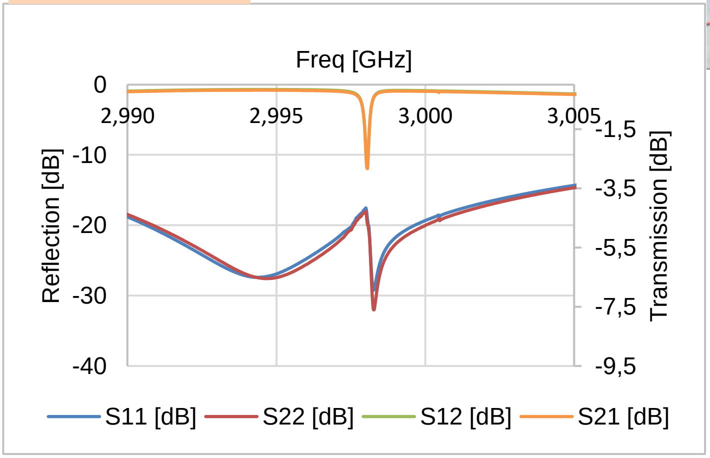


The frequency difference of 15 KHz in the two polarizations would reduce the PAF of SPC by 2%

HFSS

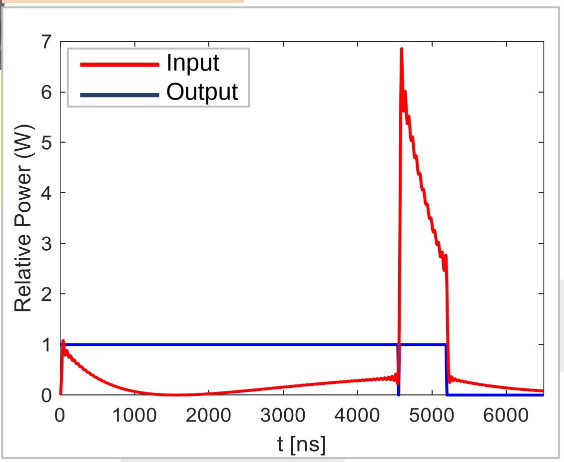


After Tuning



	SPC (HFSS)	SPC (Fabricated)
S11 (dB)	-59	-47
S21(dB)	-58	¯48
S31 (dB)	-3.01	-3.02
S32 (dB)	-3,01	-3.02
Phase Diff.	90.09^{o}	89.3^{o}

Fabricated



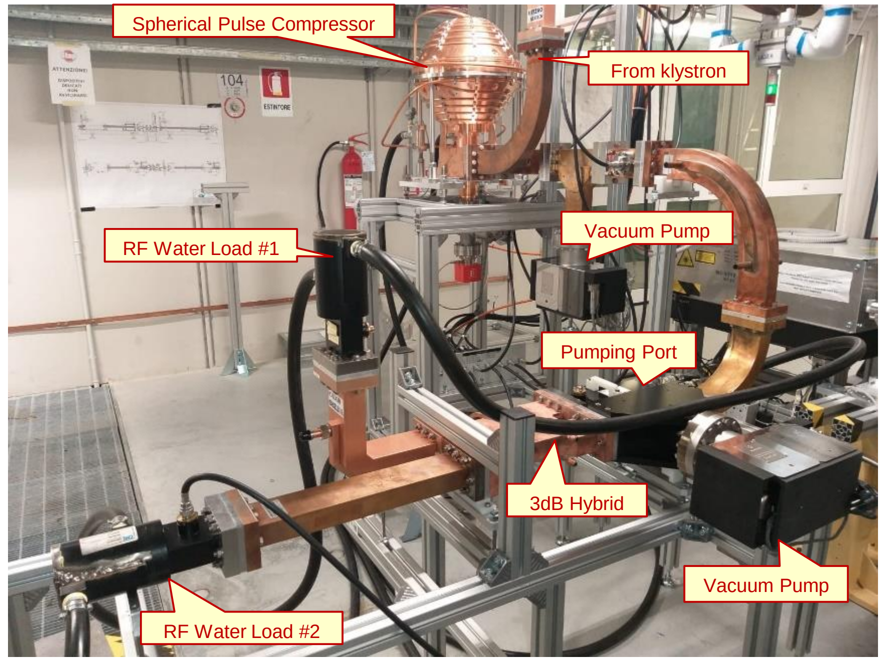
The Spherical Pulse Compressor Conditioning-High Power Opr.

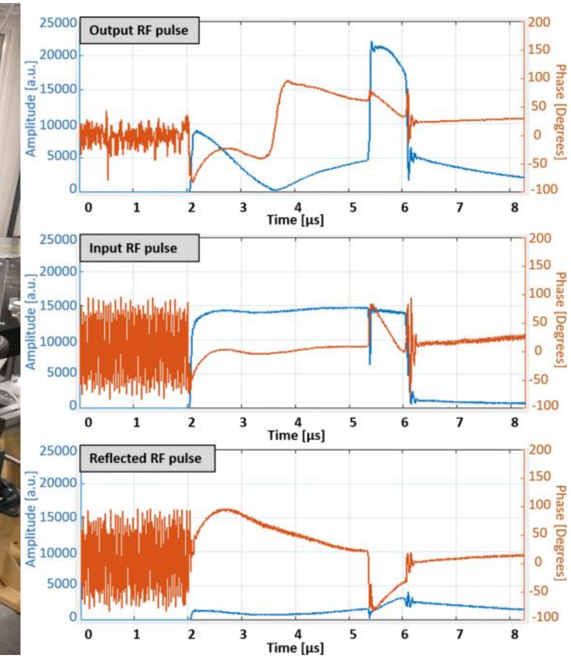
Phase I (90 MW)

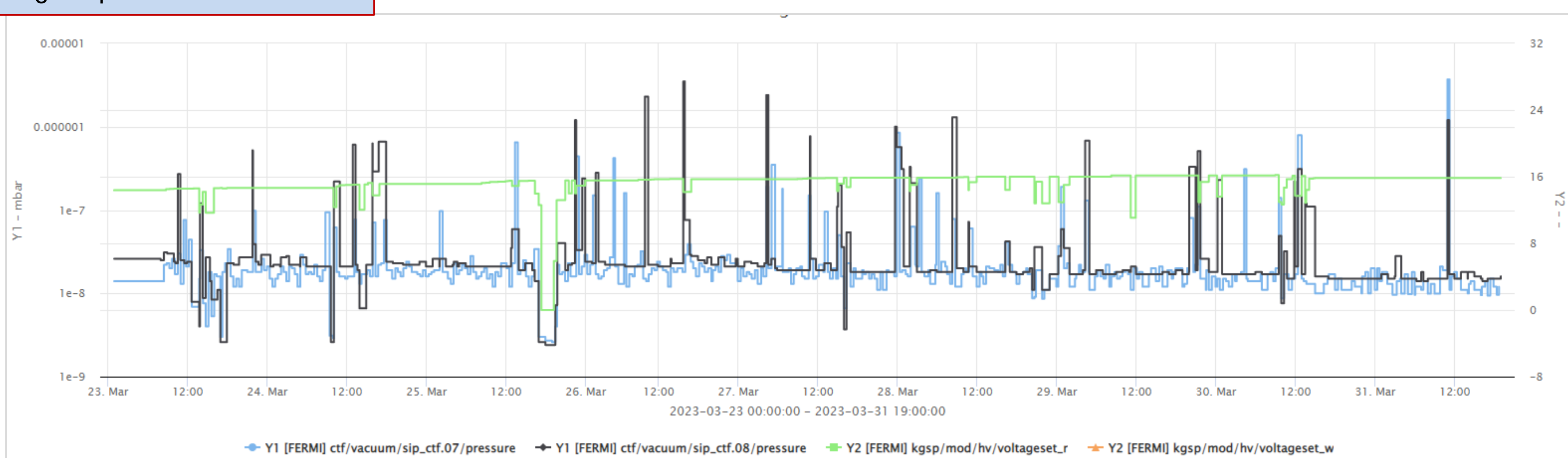
- Rep. Rate: 50 Hz
- Start Date: 06-12-2022
- End Date: 21-12-2022
- Output power: 90MW, 700 ns
- Input power: 26 MW, 4000 ns
- Operating temperature: 32.25 ^{o}C

Phase II (100 MW)

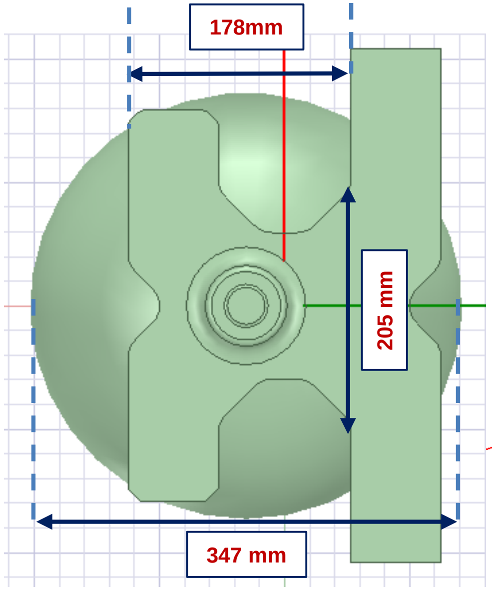
- Rep. Rate: 50 Hz
- Start Date: 23-03-2023
- End Date: 31-03-2023
- Output power: 100 MW, 700 ns
- Input power: 29 MW, 4000 ns
- Operating temperature: 31.47 ^{o}C

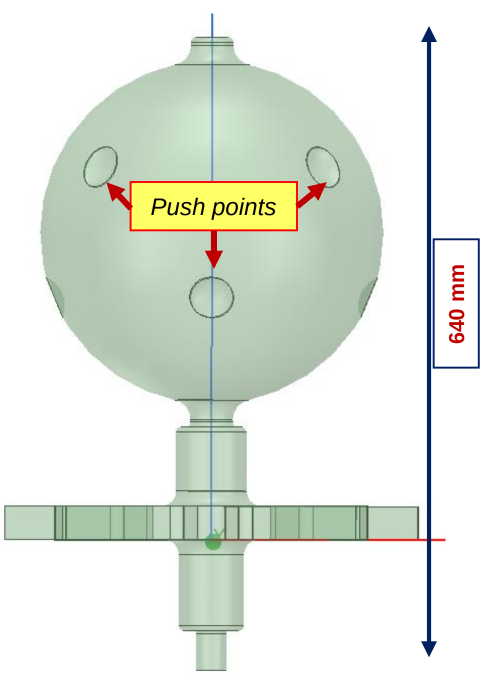


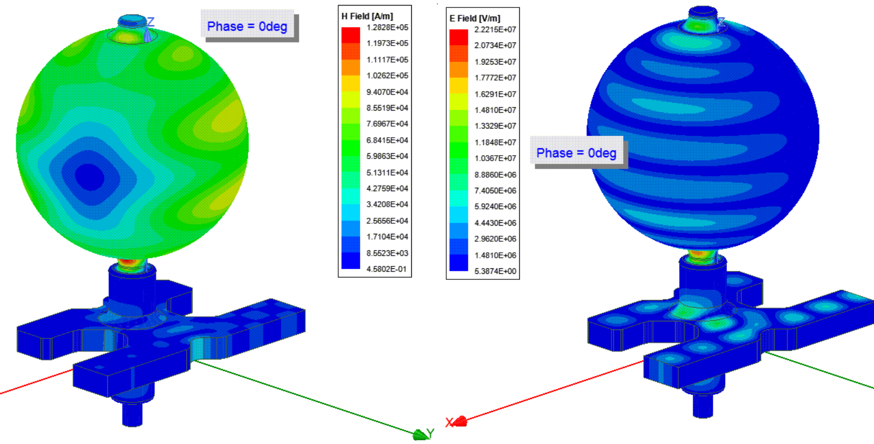


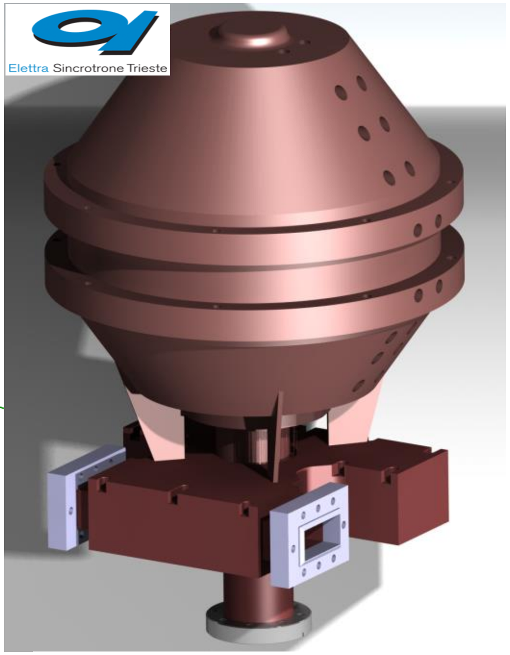


The Spherical Pulse Compressor Version 2.0

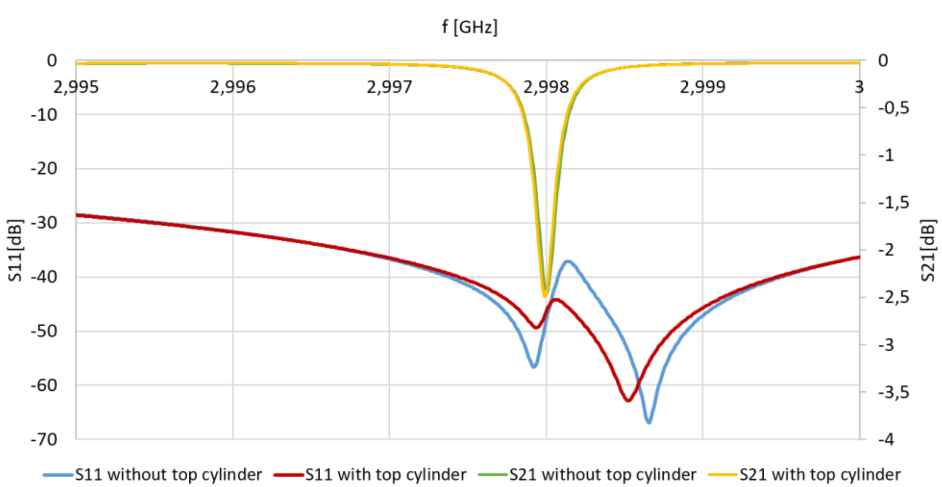


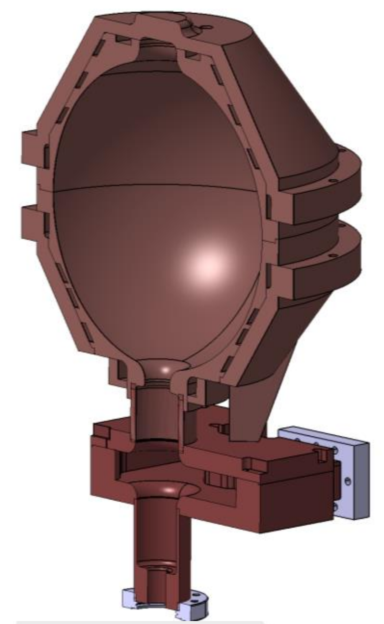






RF Parameters		
f_0	2.99801	GHz
Nominal Temperature	35	^oC
Mode	TM13	
Q0	≈140000	
Coupling Coefficient	7.1±0.1	
E @ 45 MW	29.79	MV/m
H @ 45 MW	130	kA/m

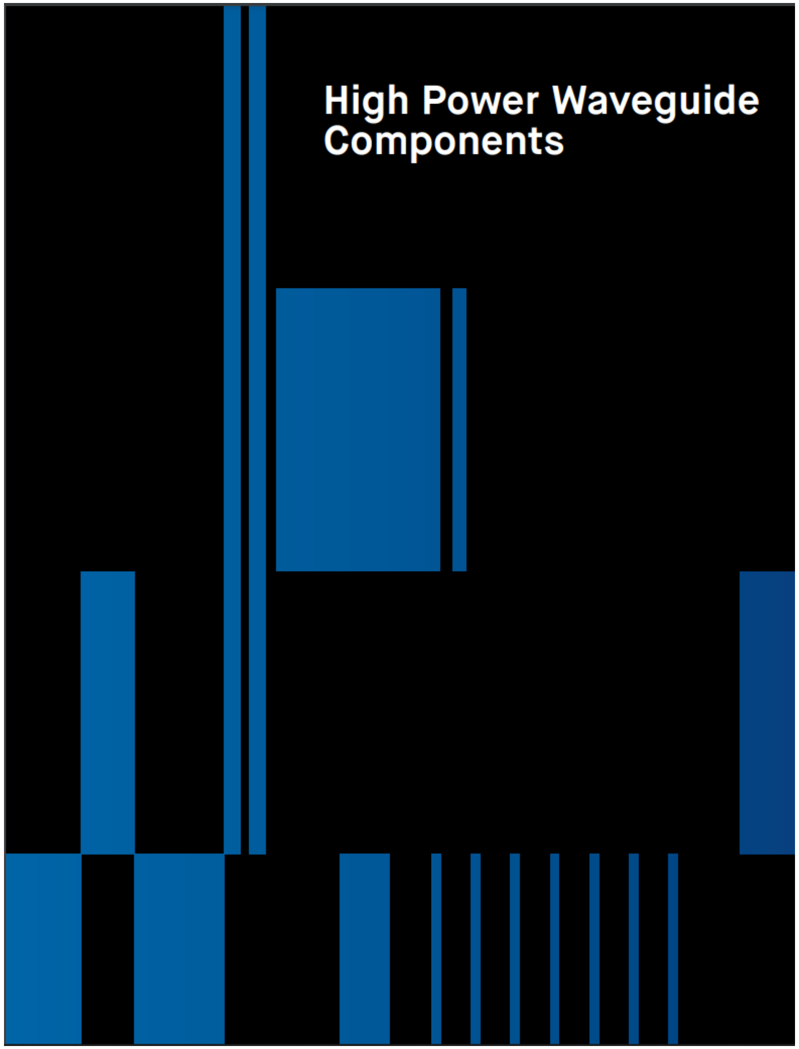


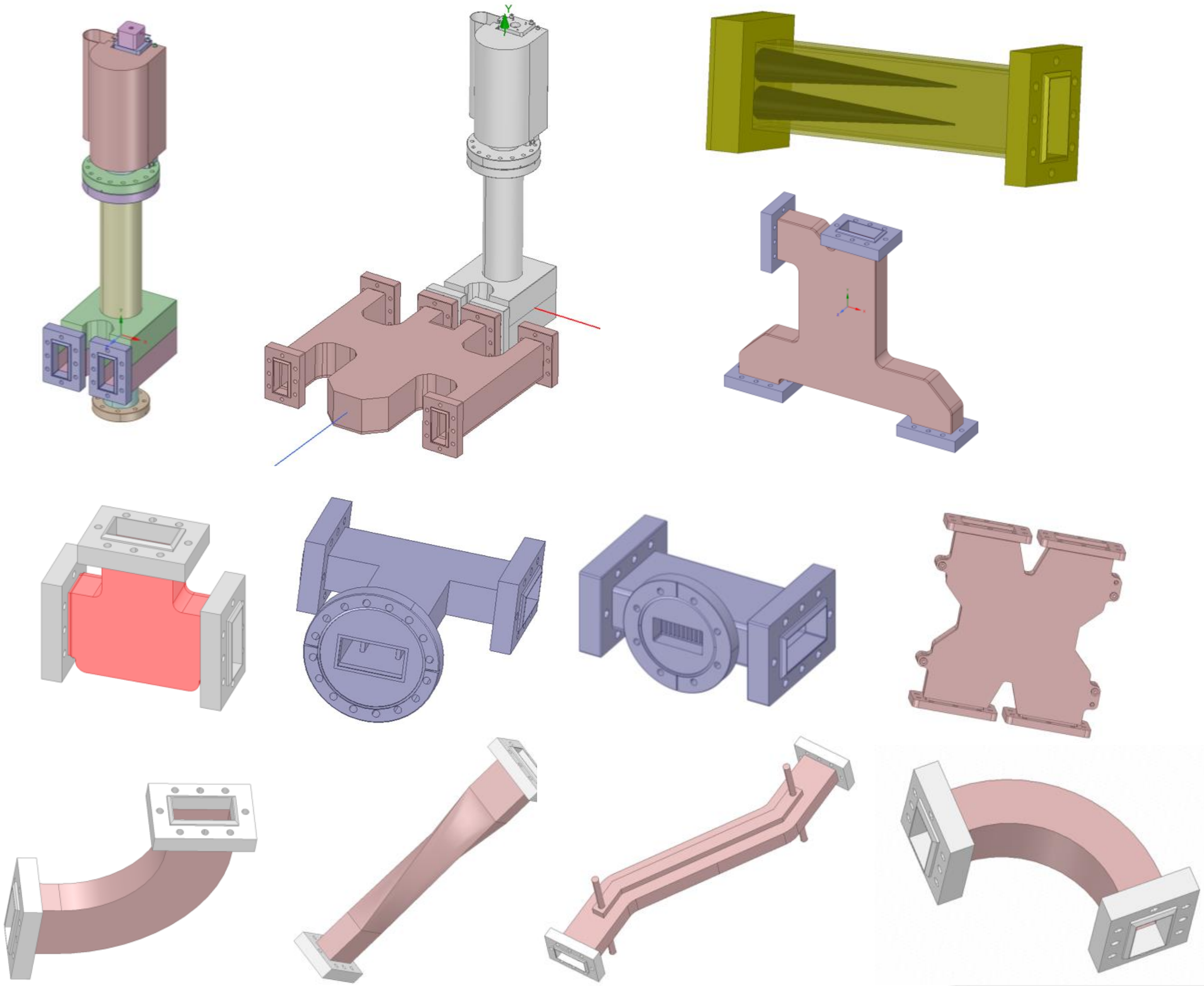


nuaman.shafqat@elettra.eu

Elettra Sincrotrone Trieste

Elettra for Industry





CONCLUSIONS

Conditioning of 1st 3.0m HG structure

- First 3.0m HG structure is succesfully conidtioned at the cavity test facility of Elettra up to an acc. gradient of **30 MV/m** with the the BDR of $6 \times 10^{-8}\ bpp/m$.

Installation of HG structures at FERMI linac

- One HG module consisting of two HG structures is installed at the FERMI linac in **September 2022** and 2nd HG strcuture is under conditioning.

S-Band Spherical Pulse Compressor

- The first prototype of S-band spherical pulse compressor has been successfully conditioned up to **100 MW** output RF power with the pulse length of **700 ns** at the cavity test facility of Elettra.

ACKNOWLEDGEMENTS

Special thanks to...

- **Luca Giannessi, Claudio Masciovecchio, Michele Svandrlik -** FERMI, Elettra
- **Walter Wuensch, Alexej Grudiev, Ping Wang -** CERN
- **M. Pedrosi, P. Craievich, R. Fortunati, F. Marcellini, R. Zennaro**- Paul Scherrer Institute (PSI)

Thank you!

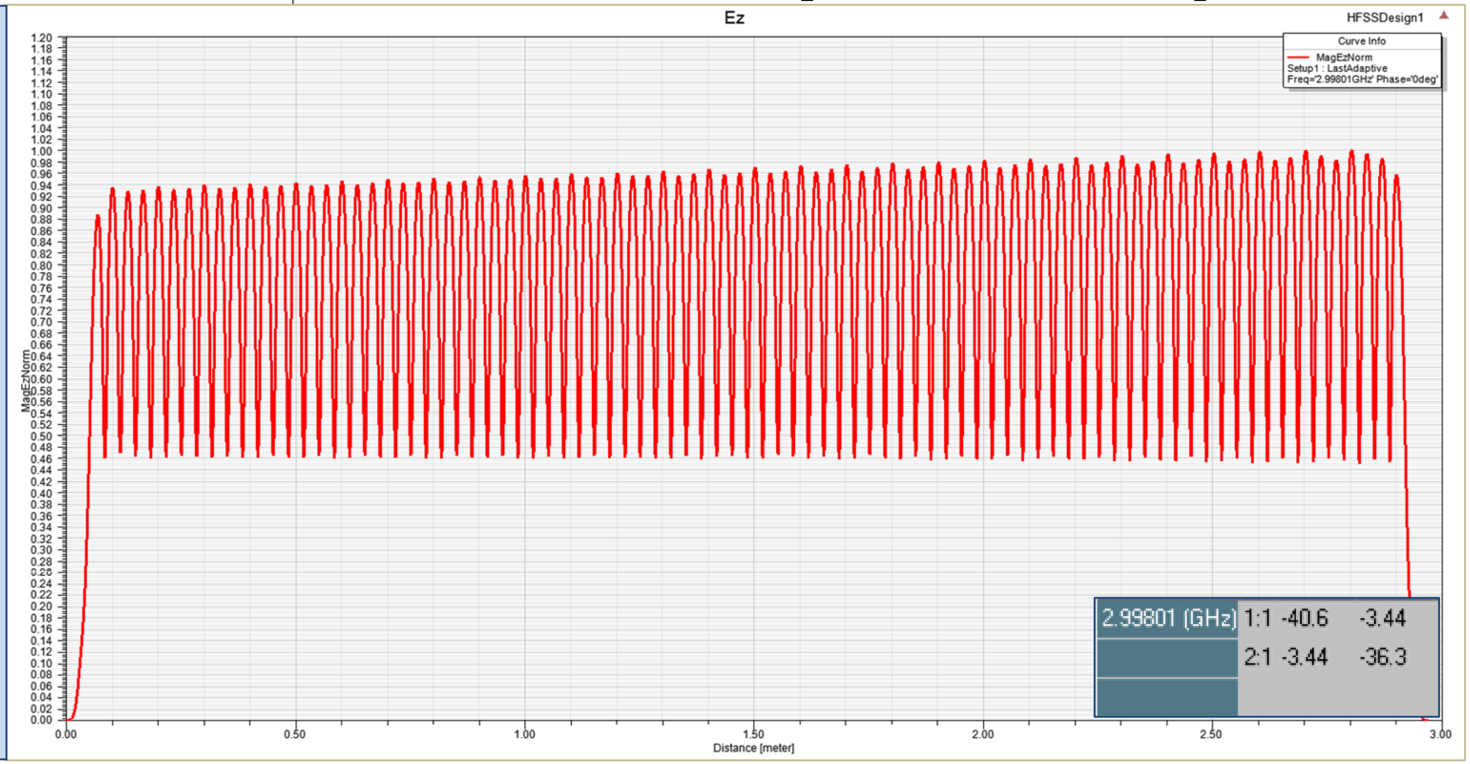
www.elettra.eu

Backup Slides

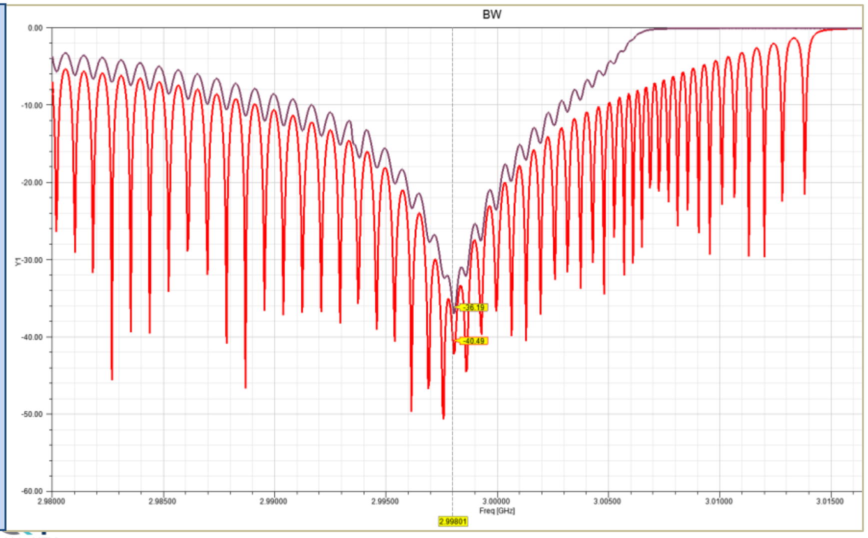
Elettra Sincrotrone Trieste

RF Analysis of Full HG Structure (3.0 meter)

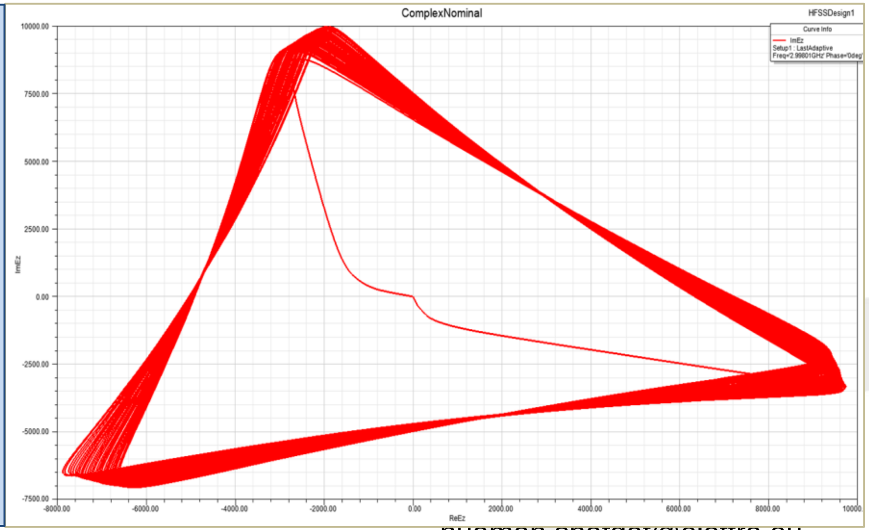
Normalized Magnitude of Ez



Bandwidth



ImEz vs ReEz

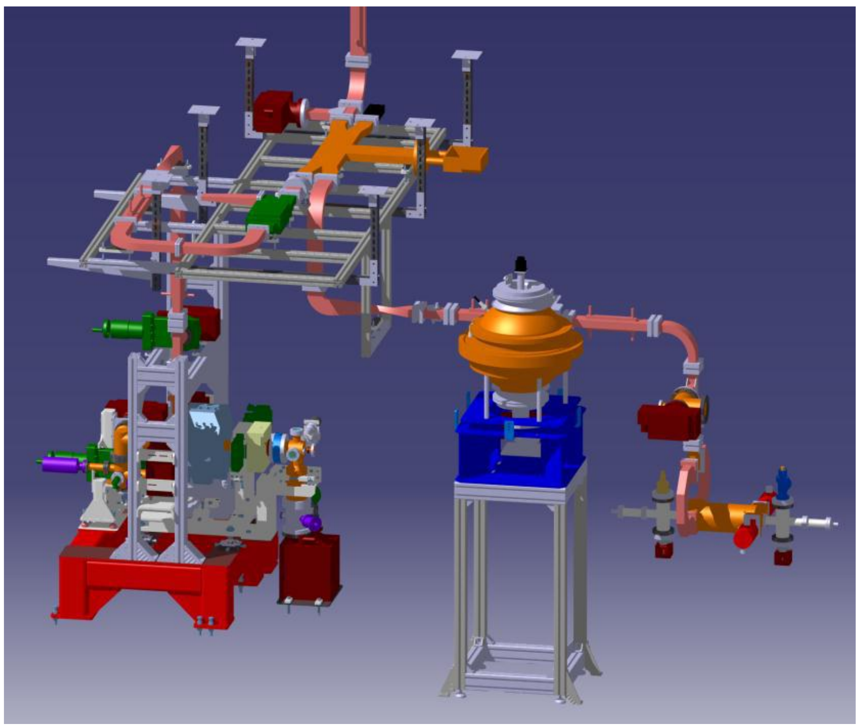


N. Shafqat et al., "Design and high-power test of a short prototype of high gradient S-band accelerating structure for the FERMI free electron laser linac upgrade")", *Nuclear Instruments and Methods in Physics Research A*, vol. 979, Nov. 2020

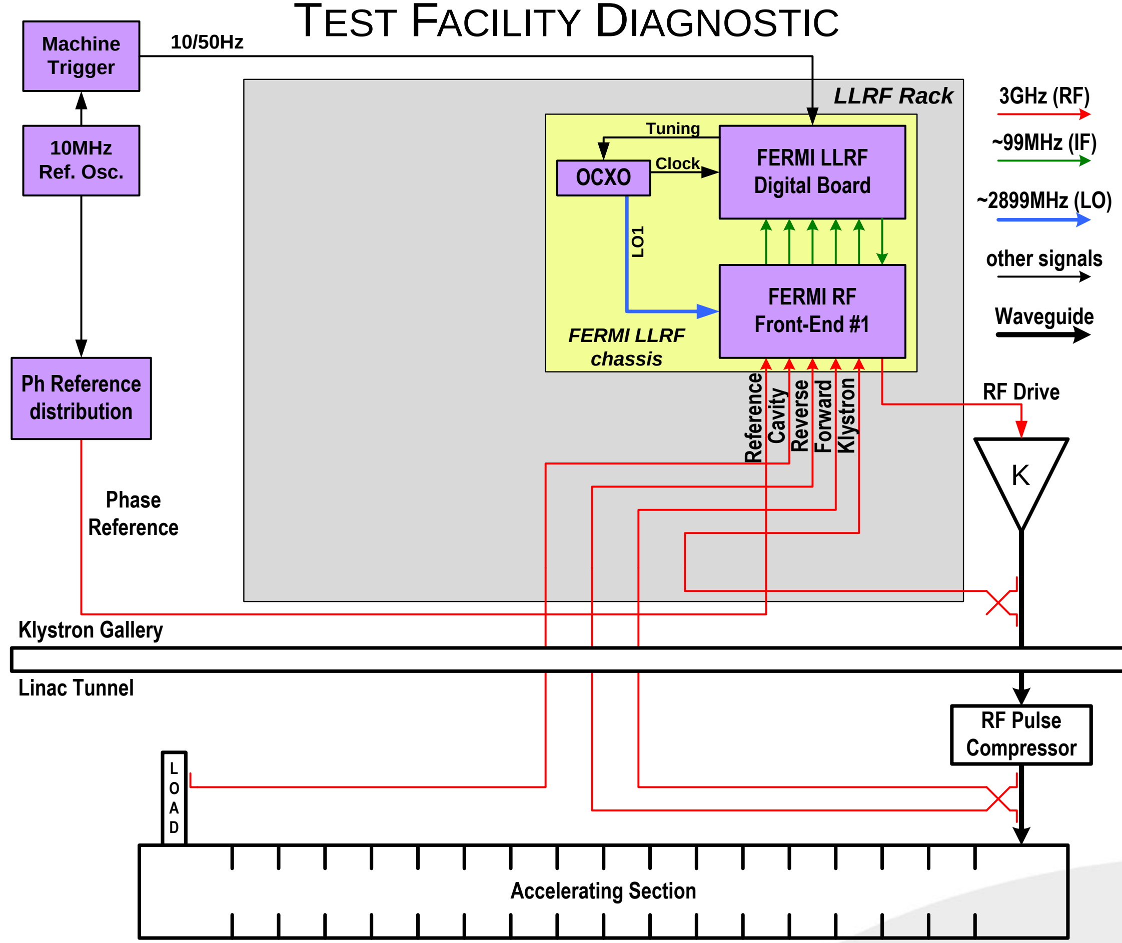
FERMI CAVITY TEST FACILITY

FERMI linac stations hot spare, has been upgraded to act also as a complete S-Band RF Cavity Test Facility (CTF)

TEST FACILITY @ ELETTRA



TEST FACILITY DIAGNOSTIC



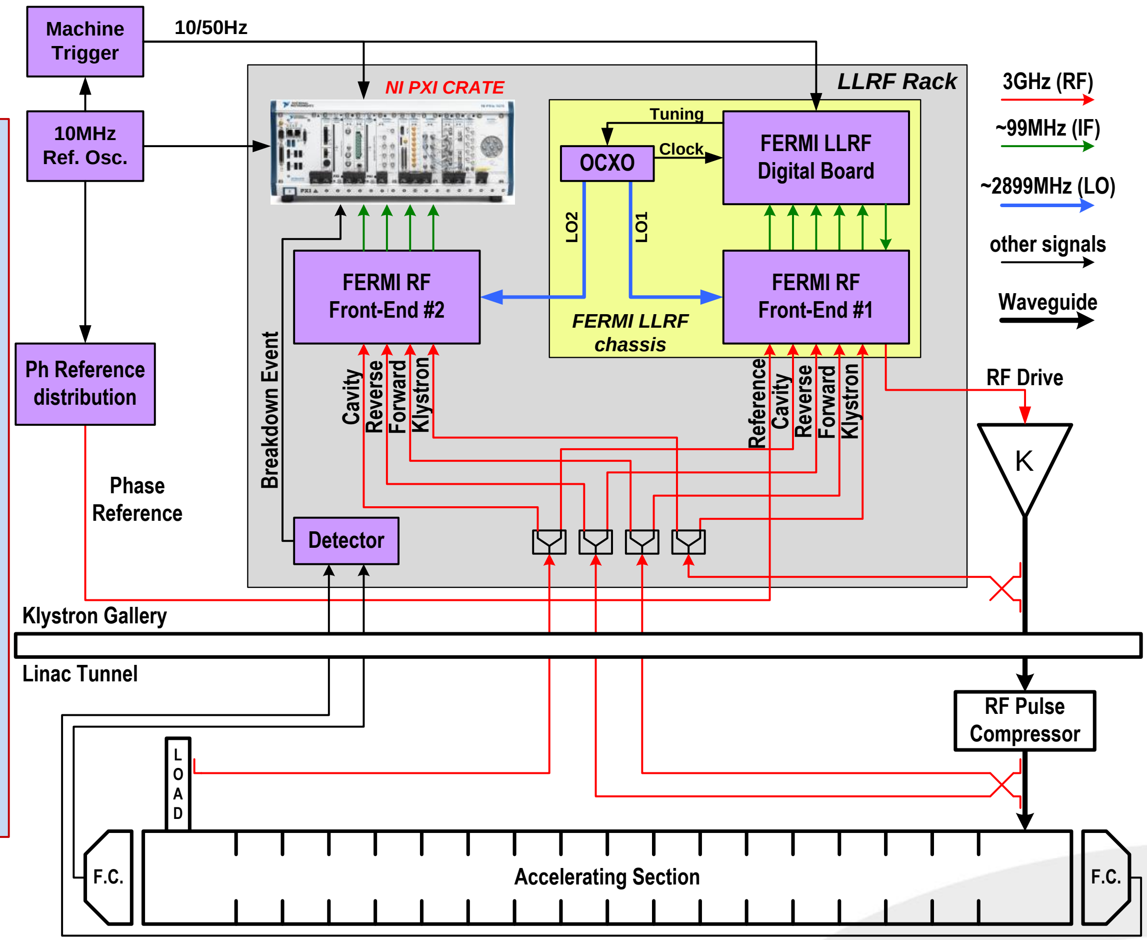
N. Shafqat et al., "Commissioning of S-Band cavity test facility at Elettra for conditioning of high gradient structures for the FERMI Linac upgrade" , *in Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, JACOW-IPAC19-WEPRB021

FERMI CAVITY TEST FACILITY

FERMI linac stations hot spare, has been upgraded to act also as a complete S-Band RF Cavity Test Facility (CTF)

TEST FACILITY @ ELETTRA

- Test of Standing Wave structures/RF Guns to 25MW peak power.
- Test of Travelling Wave structures & RF components up to 150 MW peak power.
- Hardware for breakdown diagnostic is subset of CERN breakdown diagnostic
- National Instrument (NI) hardware is integrated with FERMI LLRF for breakdown rate measurements and localization



N. Shafqat et al., "Commissioning of S-Band cavity test facility at Elettra for conditioning of high gradient structures for the FERMI Linac upgrade" , *in Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, JACOW-IPAC19-WEPRB021

Elettra Sincrotrone Trieste

Complete Conditioning Breakdown Locations